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Destruction of VOCS (Volatile Organic Compounds) by a Catalytic Paint Drying (Infrared) Device

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DESTRUCTION OF VOCS BY A CATALYTIC PAINT DRYING (IR) DEVICE

by

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16. ABSTRACT The report gives results of tests of a device that catalytically oxidizes fuel to generate infrared (IR) radiation as a new technology for paint drying and curing. During its operation, the device (introduced by SUNKISS Thermoreactors, Inc.) also oxidizes some of the paint solvents that are evaporated in the oven, thus reducing overall emissions of volatile organic compounds (VOCs) into the atmosphere. The system used to test the SUNKISS device was constructed at the University of Central Florida (UCF). It consists of flow control and measuring devices, analytical equipment, and a 1 cu m chamber in which the SUNKISS device was mounted. Three paint solvents--hexane, methyl ethyl ketone (MEK), and toluene--were dispersed in air streams that flowed through the test chamber at various rates. The solvent destruction efficiency of the device was shown to be a strong function of the air residence time in the chamber, but was independent of VOC concentration. Hexane and MEK behaved similarly, while toluene was more reactive. Observed destruction efficiencies ranged from < 20% to > 50%.

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ABSTRACT

Volatile Organic Compounds (VOC's) are emitted from a number of different types of sources, one of which is paint drying and curing ovens. A device that catalytically oxidizes fuel to generate infrared (IR) radiation recently has been introduced by SUNKISS Thermoreactors, Inc., as a new technology for paint drying and curing. During its operation, the device also oxidizes some of the paint solvents that are evaporated in the oven, thus reducing overall emissions of VOC's into the atmosphere.

A system was constructed at the University of Central Florida (UCF) to experimentally test the SUNKISS device, in order to quantify its VOC destruction capabilities. The system consisted of flow control and measuring devices, analytical equipment and a one cubic meter chamber in which the SUNKISS device was mounted. Three paint solvents-hexane, methyl-ethyl-ketone (MEK), and toluene - were dispersed in air streams that flowed through the chamber at various rates. The solvent destruction efficiency of the device was shown to be a strong function of the air residence time in the chamber, but was independent of VOC concentration. Hexane and MEK behaved similarly while toluene was more reactive. Observed destruction efficiencies ranged from less than 20% to above 50%.

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ABBREVIATIONS AND SYMBOLS

ABBREVIATIONS

cfm - cubic feet per minute
cm - centimeters
CO - Carbon Monoxide
CSTR - Continuous stirred tank reactor
DGM - dry gas meter
FCD - final control device
FID - flame ionization detector
GC - gas chromatograph
H_2 - hydrogen
IR - infrared radiation
lpm - liters per minute
MEK - methyl-ethyl-ketone
mm - millimeters
N_2 - nitrogen
ppm - parts per million
psi - pounds per square inch
psig - pounds per square inch (gage)
QA/QC - quality assurance/quality control
UCF - University of Central Florida
VOC - volatile organic solvent
WTM - wet test meter

SYMBOLS

C_e - exit concentration
C_o - inlet concentration
E - destruction efficiency
k - constant
n_e - exit molar flow rate
n_o - inlet molar flow rate
P - pressure
Q - volumetric gas flow rate
R - ideal gas law constant
T - temperature
t_R - residence time

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SECTION 1

INTRODUCTION

BACKGROUND

Volatile Organic Compounds (VOC) are emitted from a number of different types of sources, one of which is painting/surface coating operations. Substantial amounts of VOC can be in the spray booth and in the flash-off area. Significant amounts of VOC can also originate from the drying and curing oven. In conventional ovens, items are dried by hot air or by electric infrared lamps. The solvents that evaporate are discharged to the atmosphere with the dryer effluent air unless that air is routed through a Final Control Device (FCD) such as an incinerator. Solvent concentrations in the oven exhaust air are typically in the range of 100-1000 parts per million (ppm).

The amounts and types of VOC emitted from any process depend greatly on the type of paint, the type of process, and the configuration and rate of air flow through the paint booth, flash dryer and oven. Many VOC are photochemically reactive and can contribute to high oxidant levels in the ambient air. As a result, many large painting/coating operations have been required to reduce emissions of VOC to the atmosphere.

Recently, a novel type of paint drying device was introduced commercially. It works by oxidizing fuel gas on a catalyst and emitting infrared radiation in wavelengths absorbed by paint pigments. A number of such

devices are placed in the oven and oriented towards the painted parts to achieve paint drying and curing. According to tests by the manufacturer, the SUNKISS units achieve significant energy savings compared to conventional hot air or infrared (electric) lamp ovens. Much of the energy savings results because the required air flow through the oven is less than with a conventional hot air oven. Lower air flows means less energy usage in the FCD as well. Recent installations of the SUNKISS system include several automotive, bus and truck painting facilities in the U.S. and Canada.

Another benefit of the device is that some of the solvent vapors in the oven are oxidized on the catalytic surface during the drying process. Because of this concurrent VOC destruction, total mass emissions rates of VOC from the oven can be reduced, perhaps substantially enough to eliminate the need for an FCD. The degree of VOC destruction was of interest to the U.S. Environmental Protection Agency and the American Electroplaters' Society because of the potential benefits of the device to the environment and to industry.

OBJECTIVES

The main objective of the study conducted at UCF was to quantify the VOC destruction efficiency of the SUNKISS device under controlled laboratory conditions. In order to achieve this main objective, two main sub-tasks had to be accomplished. A test system including a pilot-scale oven had to be designed and constructed, and then several solvents had to be tested under various operating conditions.

Secondary objectives were (1) to demonstrate the absorption of IR by a painted surface, (2) to test the effect on the VOC destruction efficiency of a painted object emplaced in the oven, and (3) to test the effectiveness of recent engineering modifications (namely, a higher pressure fuel jet and thicker catalyst pad) on the VOC destruction efficiency.

SECTION 2

CONCLUSIONS

1. The SUNKISS unit oxidizes various volatile organic compounds thus reducing potential VOC emissions by anywhere from less than 20 to over 50 percent.

2. The percent VOC destruction efficiency is independent of VOC concentration, thus the mass rate of destruction is higher at higher VOC concentrations.

3. The percent VOC destruction efficiency increases with increasing residence time in the oven (with decreasing air flow through the oven).

4. A very small amount of CO is emitted from the device along with a small amount of uncombusted propane fuel; at lower air flow rates, the amounts of CO and propane emitted are higher than at the high air flow rates.

5. The thicker catalyst pad combined with a higher pressure fuel injection jet reduces propane and CO emissions, and enhances VOC destruction slightly.

6. The infrared radiation emitted by the device is absorbed by paint pigments causing a substantial increase in the surface temperature of the painted part and promoting the drying and curing process.

SECTION 3

RECOMMENDATIONS

1. Although the SUNKISS technology can contribute significantly towards VOC control from painting/coating operations, destruction efficiencies are not in the high (80-95%) ranges that are typically required of Final Control Devices. Therefore, it is recommended that the U.S. EPA not fund a full scale demonstration test at this time.

2. Consideration should be given by the manufacturer to modify the device to route some of the oven air into and through the catalyst pad rather than across the front face.

SECTION 4

EXPERIMENTAL EQUIPMENT AND PROCEDURES

SYSTEM DESCRIPTION

Overview

The experimental apparatus constructed specially for this project is shown schematically in Figure 1. Basically, the equipment consisted of air flow measurement and control devices, a solvent saturator system, a reaction chamber, and sampling and analytical apparatus. House air, filtered through glass wool, silica gel, and activated carbon, flowed through at least two rotameters in parallel. A measured rate of air was bubbled through liquid solvent in a double saturator system and produced a saturated stream of solvent vapor in air at 0°C. That stream was diluted by another measured flow of pure air to create a stream of air at a desired concentration and desired total flow rate that then was fed into the reaction chamber.

The reaction chamber was a welded steel box enclosing approximately one cubic meter of space. The SUNKISS device was mounted on the side opposite the air inlet and an exhaust stack was mounted on the top on the inlet end of the chamber. The SUNKISS Unit has an internal 60 cfm fan that provided some mixing of the air in the chamber, and was augmented by a 200 cfm fan mounted co-axially with the air flow inlet. The SUNKISS fan blew chamber air across the front face of the catalyst pad; some of the VOC was adsorbed and oxidized on the surface of the catalyst. A schematic diagram of a SUNKISS Unit is

presented in Figure 2.

Several sample lines and thermocouples were placed at strategic locations in the chamber. Samples were withdrawn by a vacuum pump through a gas sampling valve mounted on an ANTEK 2400 chromatograph equipped with a flame ionization detector. Samples were also routed to a Thermoelectron Model 48 CO analyzer.

Flow Measurement and Control

Air flow measurement and control was accomplished with manually controlled rotameters, each of which was calibrated carefully with either an accurate wet test meter or an accurate dry gas meter. All rotameters were manufactured by Fisher and Porter. Rotameter calibration is discussed later in this section. UCF house air first was passed through a filter package consisting of a layer of glass wool, followed by granular activated carbon, followed by silica gel, and then by a final layer of glass wool. The air was then split into four possible streams, the flow rate of each of which could be individually measured and adjusted. The piping was arranged so that the main air flow rate bypassed the solvent saturator system, while one, two, or three of the other streams could be routed through the saturator. Thus, almost any combination of total air flow rate (from 2 cfm to 8 cfm) and solvent-in-air concentration from 200 to 2000 ppm could be created and maintained during the operation.

Solvent Saturator System

The purpose of the solvent saturator system was to produce a reproducible and reasonably accurately known concentration of VOC in air. A wide range of concentrations could be produced by blending a stream of solvent-free air with an independently controlled stream of completely saturated air.

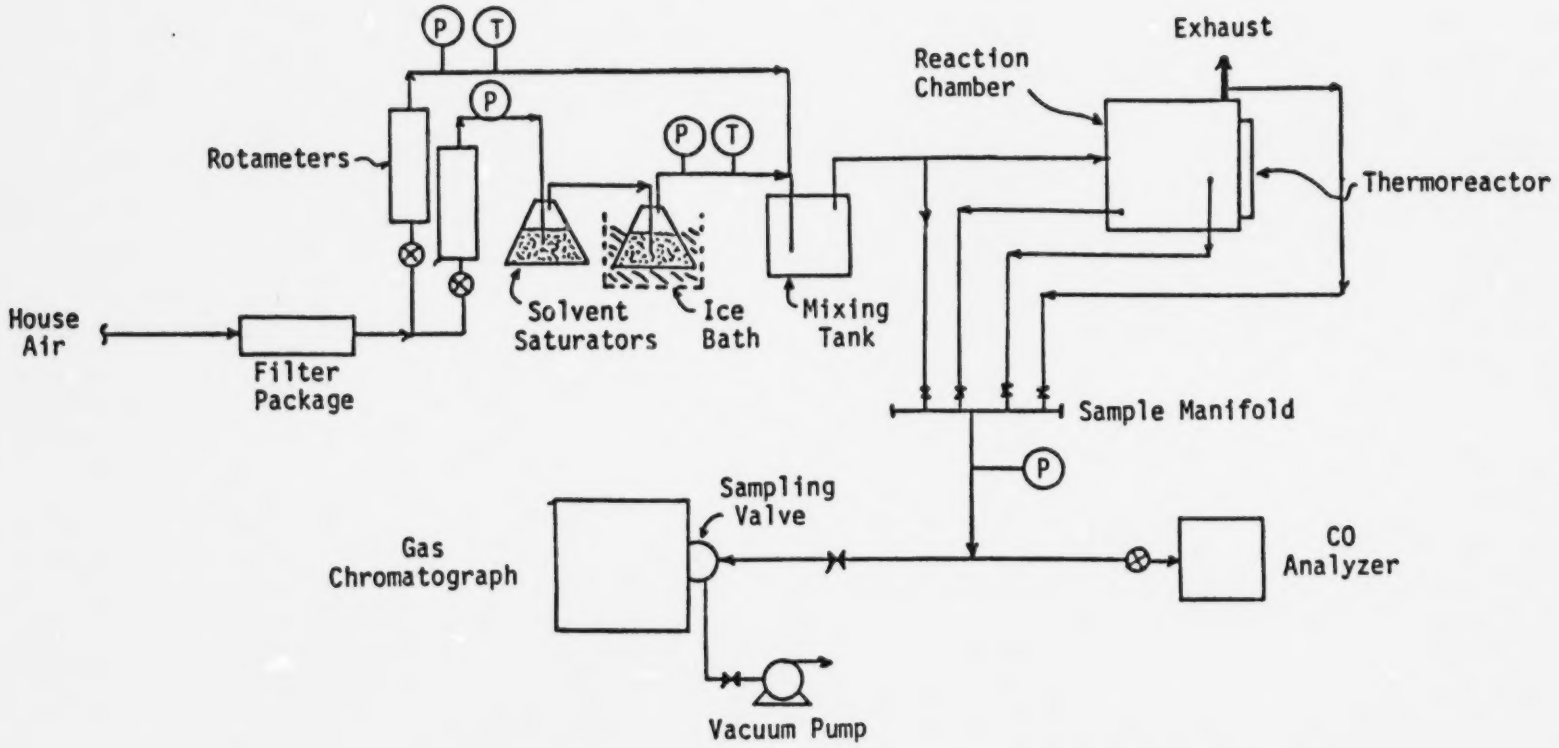


Figure 1 Schematic Flow Diagram of System

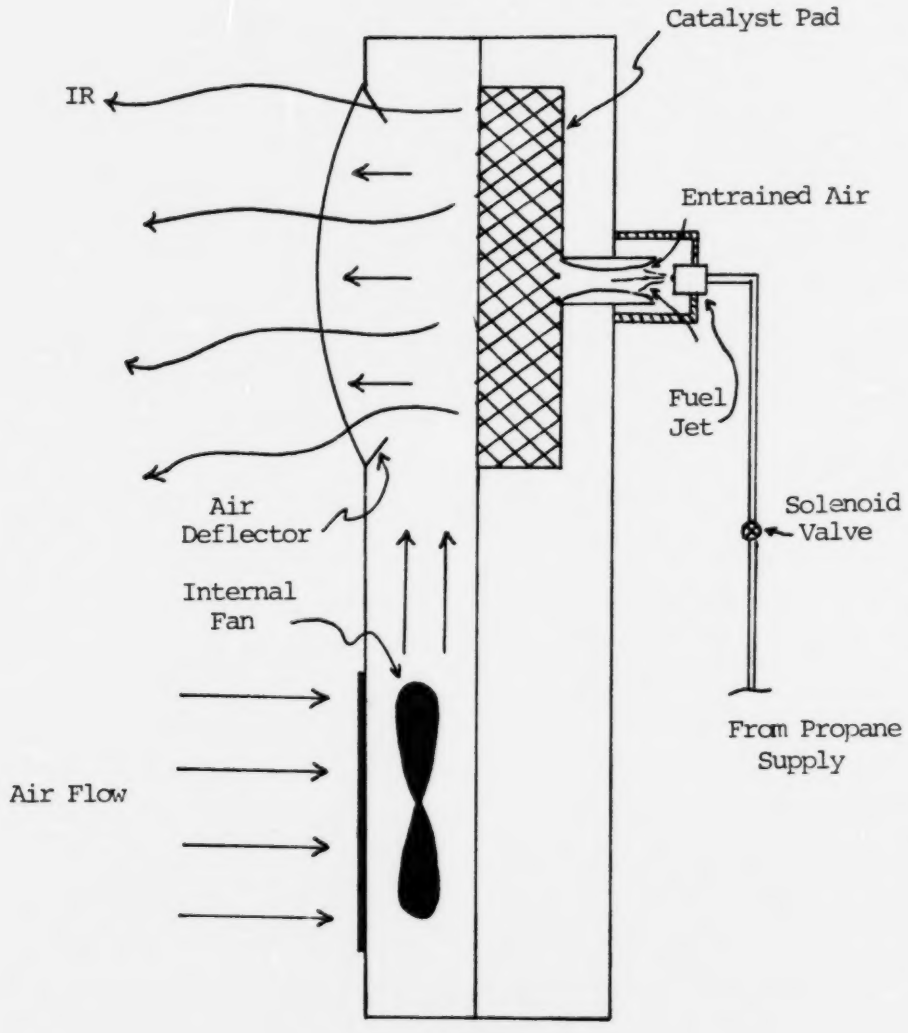


Figure 2 Schematic Diagram of SUNKISS Device

Because of the difficulty, expense, and uncertainty associated with obtaining cylinders of VOC in air for calibration purposes, we believed that it was best to calibrate the VOC analytical instrument (a GC-FID) by preparing flow streams of known concentrations of VOC in air. The method of mixing vapor-saturated and dry streams of air in pre-set flow ratios was used to achieve known concentrations for instrument calibration. This method has been used successfully in the past and is summarized below.

Primary air was passed through a dual saturator system consisting of two 1000 ml Erlenmeyer flasks, teflon tube bubblers, and a copper cooling coil. Saturation of 40-50% was obtained in the first stage which operated at 25°C. The air then was passed through copper coils submerged in a 10°C water bath and then into a second saturator. The second saturator was surrounded by a 0°C water-ice bath. In the second stage, 100% saturation was achieved due to additional vapor-liquid contact, and probable condensation of VOC picked up in the first saturator. Dilution air was metered through a second calibrated rotameter by-passing the saturator system and was blended with the saturated stream to achieve desired concentrations. A mixing tank insured complete mixing prior to the combined stream being passed to the reaction chamber.

Reaction Chamber

Before a detailed design of the test chamber was undertaken, the available literature on the SUNKISS Thermoreactor was researched. Test reports from Factory Mutual Research, CRIQ, and Citroen were reviewed. Brochures from SUNKISS Thermoreactors, Inc., were reviewed and discussions were held with representatives of their company. Trip reports of visits by U.S. EPA personnel were also used in obtaining the background required to properly design the test chamber.

The chamber was designed to enclose approximately one (1.0) cubic meter of space. Because we were operating a mono (one catalyst pad) unit, our volume/unit was in excellent agreement with the Citroen test. The chamber was built from 11-gauge steel welded at all seams. Thus, it was structurally

sound, leak-proof, able to withstand all possible operating temperatures, and did not have any potential for self-emission of fumes (as plywood or composites might). The SUNKISS unit was mounted at one end of the chamber (opposite from the air entrance) on a custom-made flange with 10 wing nuts and bolts and sealed with a custom-cut high temperature gasket.

The inlet gas (the pre-mixed stream of air with a low concentration of VOC) entered through a diffuser-type entrance near the bottom of the chamber and directly across from the SUNKISS unit. Both the total inlet gas flow rate (from about 2 to 8 cfm) and the inlet VOC concentration (from about 200 to 2000 ppm) could be independently controlled. Inlet and outlet gases were monitored for concentration and temperature, plus sample ports were built into the chamber to enable samples to be taken from within the chamber itself.

A small concrete pad was designed and constructed outside the engineering building for the chamber. The area was enclosed with a chain-link fence. A steel frame was built to elevate the chamber, and connection openings were drilled through the wall of the building into environmental laboratory. Thus, while the chamber was outside, all of the analytical instruments, flow controls, etc., were inside the lab. Because the chamber was outside, its exterior was given three coats of a heavy duty, epoxy-type paint. The inside walls are simply bare steel. A small chimney was placed on the chamber to safely exhaust the effluent gases.

Sampling and Analytical System

The sampling and analytical system consisted of the sample probes and lines, thermocouples, vacuum pumps, gas chromatograph (GC), and carbon monoxide (CO) analyzer. The sample probes consisted of pieces of 1/8-inch copper tubing inserted at various locations in the chamber, including the inlet and outlet pipes. The copper tubing probes were connected by 1/8-inch nylon tubing to a sample mainfold located inside the laboratory. Gas samples were withdrawn through the tubing by a Neptune Dyna-Pump (model 4K), a

diaphragm-type oil-less vacuum pump. The pressure in the manifold was controlled by adjusting a needle valve just upstream of the vacuum pump. The pressure was measured by a Magnahelic gauge (0-5 psi) and was always controlled to the same value to ensure sampling and analytical precision.

From the manifold, the gas samples could be directed either to the GC or to the CO analyzer. The GC was manufactured by ANTEK instruments and sold by Fisher Scientific (model 2400) and was equipped with a flame ionization detector (FID). The CO analyzer was a Thermoelectron Model 48 ambient CO analyzer. The CO analyzer used a gas filter correlation NDIR principle and is designated by EPA as an equivalent reference method instrument. All VOC and CO measurements were recorded on a multispeed chart recorder. The one used in this study was a Kipp and Zonen (model BD41) 2 pen recorder. Calibration of the instruments and flow meters will be discussed later in this section.

Temperatures were measured at several points throughout the flow system and reaction chamber. All temperature measurements were made with calibrated chromel-alumel thermocouples that were connected to a Transmation LED Minitemp digital indicator (model 310-DS(P)-10).

EXPERIMENTAL PROCEDURES

The events involved in a typical experimental run are described below. All instruments (i.e., gas chromatograph, CO analyzer, chart recorder) were allowed sufficient time for warmup and stabilization as per manufacturers' instructions. The appropriate solvent was poured into the saturators and all fittings were checked for leaks. The GC column temperature was adjusted (based on experience in this study) to provide the most consistent and accurate results for each solvent used.

The individual stream flow rates to achieve desired solvent concentrations and total inlet air flow rates were adjusted via inline rotameters. To assure representative results, steady state conditions had to be obtained in the test chamber. The chamber average residence time, t_R (t_R = chamber volume/air flow rate) varied for the different flow rates. At each different flow-rate we waited a period of 4 x t_R before beginning the sample testing.

Each time a sample was analyzed for VOC, 3 or 4 samples at 1 minute intervals were analyzed and the average of the peak heights on the chart recorder was allowed to represent the true VOC concentration. Chamber inlet samples were taken as well as chamber outlets. The mean of the outlet solvent peaks was compared to the mean of the inlet tank peaks and both were recorded. CO was also measured. Propane peaks were observed and recorded as well. VOC destruction efficiencies were calculated based on the measured inlet air molar flow rate x measured VOC inlet concentration vs. calculated outlet gas molar flow rate (including propane combustion products plus and entrained air) x measured outlet VOC concentration.

The above procedure was repeated at least three times for each specific test (each air flow rate and concentration), and a final destruction efficiency was calculated as the average of all the replications.

QUALITY ASSURANCE/QUALITY CONTROL

General

In any study that results in data to be used for engineering analysis and decision, the assurance of data quality is important. Recognizing that EPA was not proposing regulations based on the data collected in this study, a QA/QC plan was developed and executed that was sufficient to ensure the validity of any conclusions, yet did not overwhelm the project with excess requirements.

With real-time samples there were no sample handling, custody, storage, or identification problems. The main QA/QC concerns were precision and accuracy of the measurements. Both of these concerns were met with careful attention to detail during the runs, and by careful calibration of all flow and analytical equipment during the first several months of the project prior to the start of data collection.

The major measurement parameters, their reference method for measurement, and their QA objectives in terms of precision, accuracy, and completeness are listed in Table 1. Precision (repeatability) is defined as a measure of mutual agreement among individual measurements of the same property, under prescribed similar conditions. Precision was expressed as a standard deviation--either as a percent of the measured value or in absolute terms, i.e., ml/m^3. It should be noted that precision was expected to be better when replicates were made of a sample during a given experimental run than when a corresponding sample was made on a replicate run. In the first case, variations occur due to the analytical equipment or procedure only, whereas in the second case, variations are possible due to flow rate or solvent differences. Our QA/QC plan was directed primarily towards the former more controllable sources of variability. While precision objectives are presented in this section, actual precision was determined by replications designed into the experimental program.

Accuracy is a measure of "trueness" or "closeness to reality" of the measurements. It is assessed by comparing the measurements with an accepted reference or true value of standards. We expressed accuracy as a percentage of the true value, 100% (X/T), where X is the measured value and T is the true value. While accuracy objectives are presented in this section, the accuracy achieved was determined by our ability to calibrate flow meters, and to calculate VOC concentrations from flow rate and vapor pressure data. The accuracy of our CO measurements was checked by purchased calibration gases that were certified ± 2% accurate.

Completeness is a measure of the amount of valid data obtained from a measurement system compared with the amount that was expected to be obtained under correct normal conditions. Completeness was not a problem in this study because all equipment performed well throughout the experimental program.

TABLE 1

Minimum Objectives for Precision, Accuracy, and Completeness of Data

Measurement Parameters	Method	Reference	Precision %	Accuracy %	Completeness %
VOC	GC-FID	a	10	80-120	95
CO	NDIR or equiv.	a	5	90-110	95
flow rate	Rotameter	b	10	80-120	95

a. Methods of Air Sampling and Analysis, 2nd ed., American Public Health Association, 1977.

b. Rotameters were calibrated in accordance with generally accepted devices, methods, and criteria, traceable to a primary standard method.

Calibration Procedures and Results

Prior to the start of experimental runs, a careful calibration program was undertaken to calibrate all flow meters and all instrumentation to ensure adequate accuracy and precision. The results demonstrated a high degree of repeatability from run to run.

Wet Test Meter--A GCA Precision Scientific wet test meter (WTM) was calibrated by a primary standard procedure as shown in Figure 3, which is in accordance with ASTM standard D-1071-55.

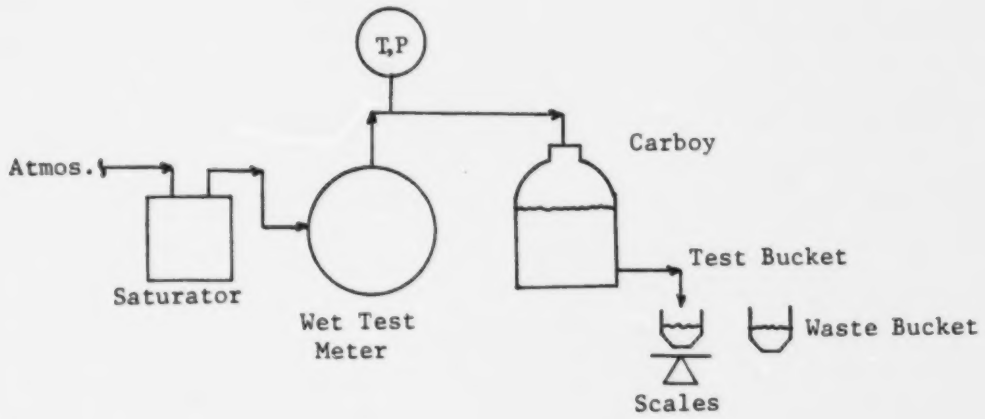


Figure 3. Calibration of a Wet Test Meter

The system was leak tested and then several preliminary trials were conducted to find the exact proper level of water to be maintained in the WTM. The volume of water displaced from the carboy was calculated to four-place accuracy by measuring the weight of water and its temperature and using its exact density. Table 2 presents the calibration data for the WTM; each point is an average of four trials. The average absolute error of the five calibration points was 0.17 percent.

TABLE 2

Calibration Data for Wet Test Meter

Meter Volume, l	Actual Volume, l	Percentage Error, %
3.0	3.013	+0.43
5.0	4.997	-0.06
7.0	6.984	-0.23
9.0	8.995	-0.06
12.0	11.99	-0.08

Dry Gas Meter--A Rockwell S-200 dry gas meter (DGM) was calibrated using the wet test meter as shown in Figure 4.

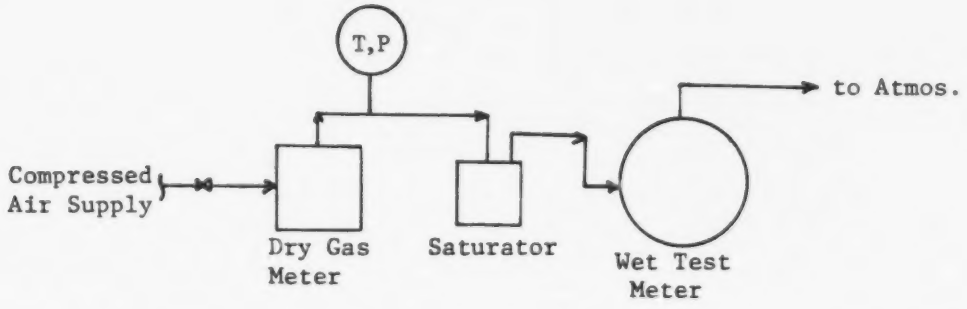


Figure 4. Calibration of a Dry Gas Meter

During initial testing, the air going through the DGM was determined to be about 70% saturated; it was brought up to 100% saturation before going into the wet test meter. The volume through the WTM was corrected back to partial saturation with water, and the dry volume was then corrected back to the temperature and pressure of the DGM to get the actual volume of gas that passed through the DGM. Table 3 presents the calibration data for the dry gas meter; each point is the average of three trials. The manufacturer's calibration curve indicated ±0.2% maximum error in the normal operating range (20 to 100% of rated capacity), and we found an average absolute error of 0.84% in the low range (5 to 20% range).

TABLE 3

Calibration Data for Dry Gas Meter

Dry Gas Meter Volume, l/min	Actual Volume, l/min	Percentage Error, %
18.68	18.63	0.27
11.69	11.81	1.0
8.40	8.47	0.83
8.23	8.30	0.84
4.74	4.80	1.25

Instrumentation Gas Rotameters--Although not critical to accomplishment of the project, it was decided that the most repeatable GC performance could be obtained by controlling the instrument gases (H_2, N_2, and air) to the same flow rates each time that instrument was turned on. To this end, three small air rotameters, manufactured by the Gilmont Instrument Company, Inc., were installed and calibrated as discussed below.

FID Air Rotameter--The rotameter used to measure the air flow rate to the FID was calibrated using the wet test meter as shown in Figure 5. The air volume that passed through the WTM was corrected for the presence of water vapor and then adjusted to the temperature and pressure in the rota-

technique. The fit was excellent as shown in Figure 6. The equation of the best fit straight line, along with the correlation coefficient (R^2) is given on the figure.

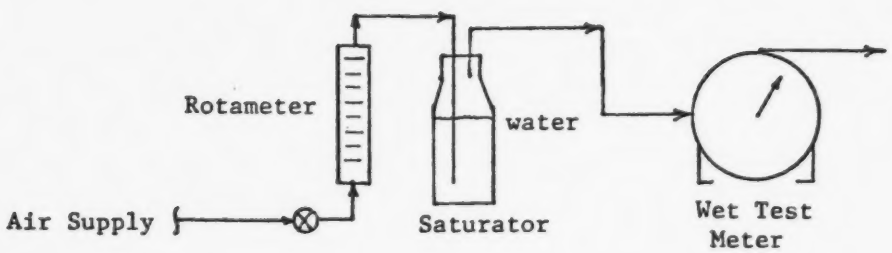


Figure 5. Calibration of a Rotameter with a Wet Test Meter

FID Hydrogen Rotameter--The rotameter used to measure the flow rate of hydrogen to the FID was calibrated using a bubble meter as shown in Figure 7.

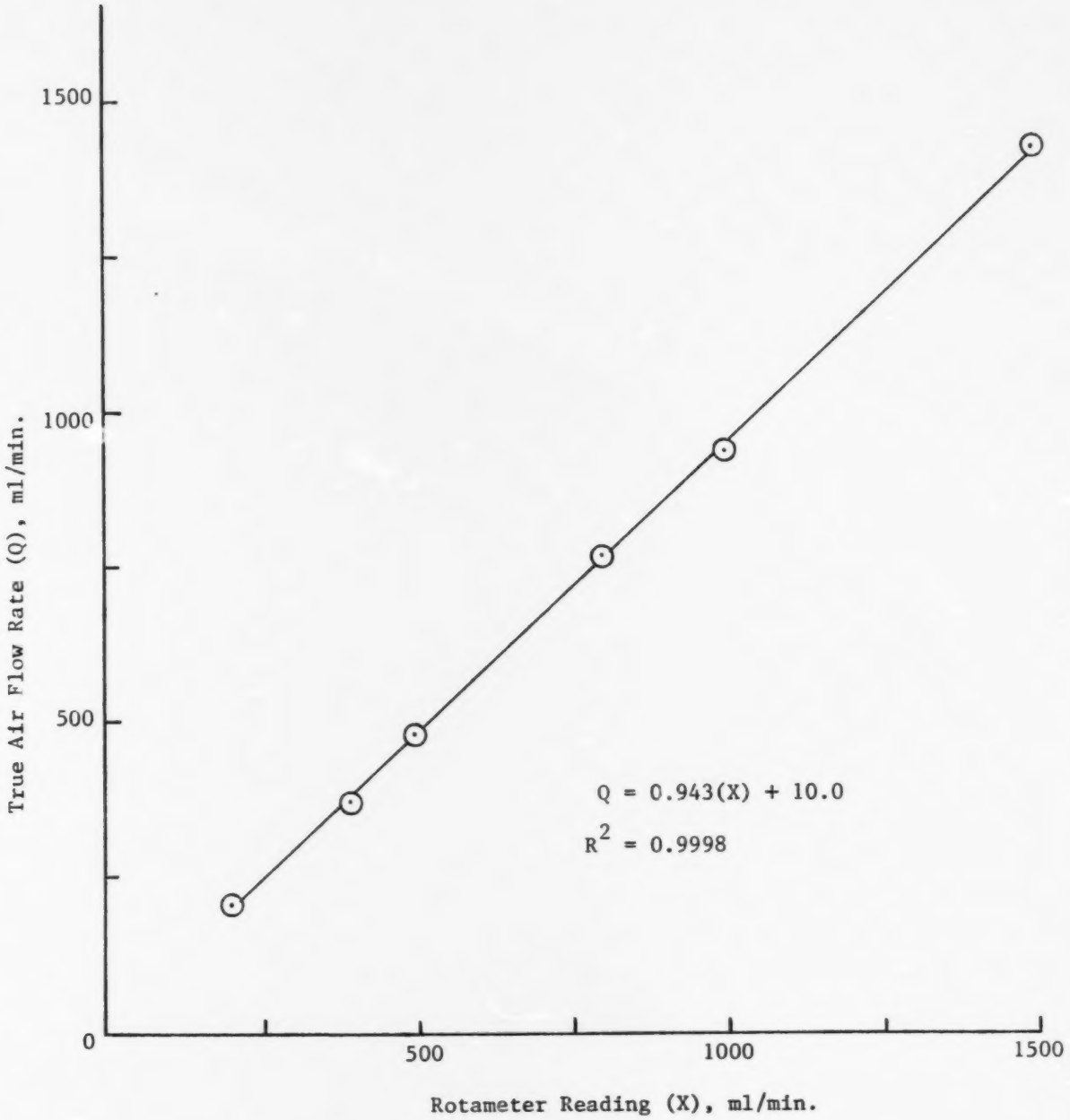


Figure 6 Calibration curve for instrument air.
(For air at T = 23°C, P = 770 mm Hg).

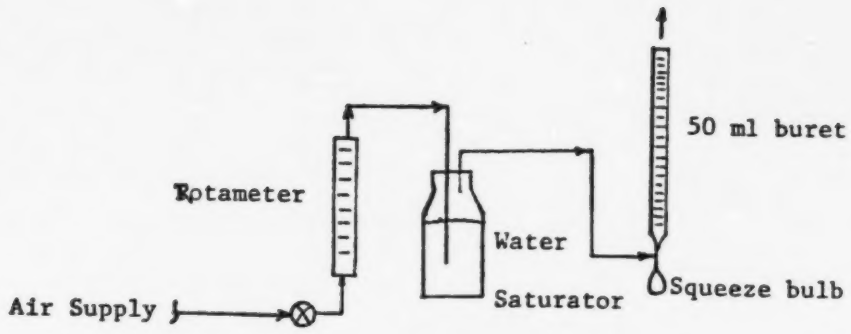


Figure 7. Calibration of a Rotameter with a Bubble Meter

After passing through the rotameter, the H_2 was saturated and passed through the bubble meter. The bubble meter volume was corrected for the presence of water vapor, and then adjusted back to the temperature and pressure in the rotameter. The calibration data were plotted and fit by a linear least squares technique. The fit was excellent as shown in Figure 8. The pertinent equation and coefficients are shown on the figure.

Carrier Gas (N_2) Rotameter--The rotameter used to measure the flow rate of nitrogen carrier gas was calibrated using a bubble meter. After passing through the rotameter, the N_2 was saturated and passed through the bubble meter. The bubble meter volume was corrected for the presence of water vapor, and then adjusted back to the temperature and pressure in the rotameter. The calibration data were plotted and fit by a linear least squares technique. The fit was excellent as shown in Figure 9. The pertinent equation and coefficients are shown on the figure.

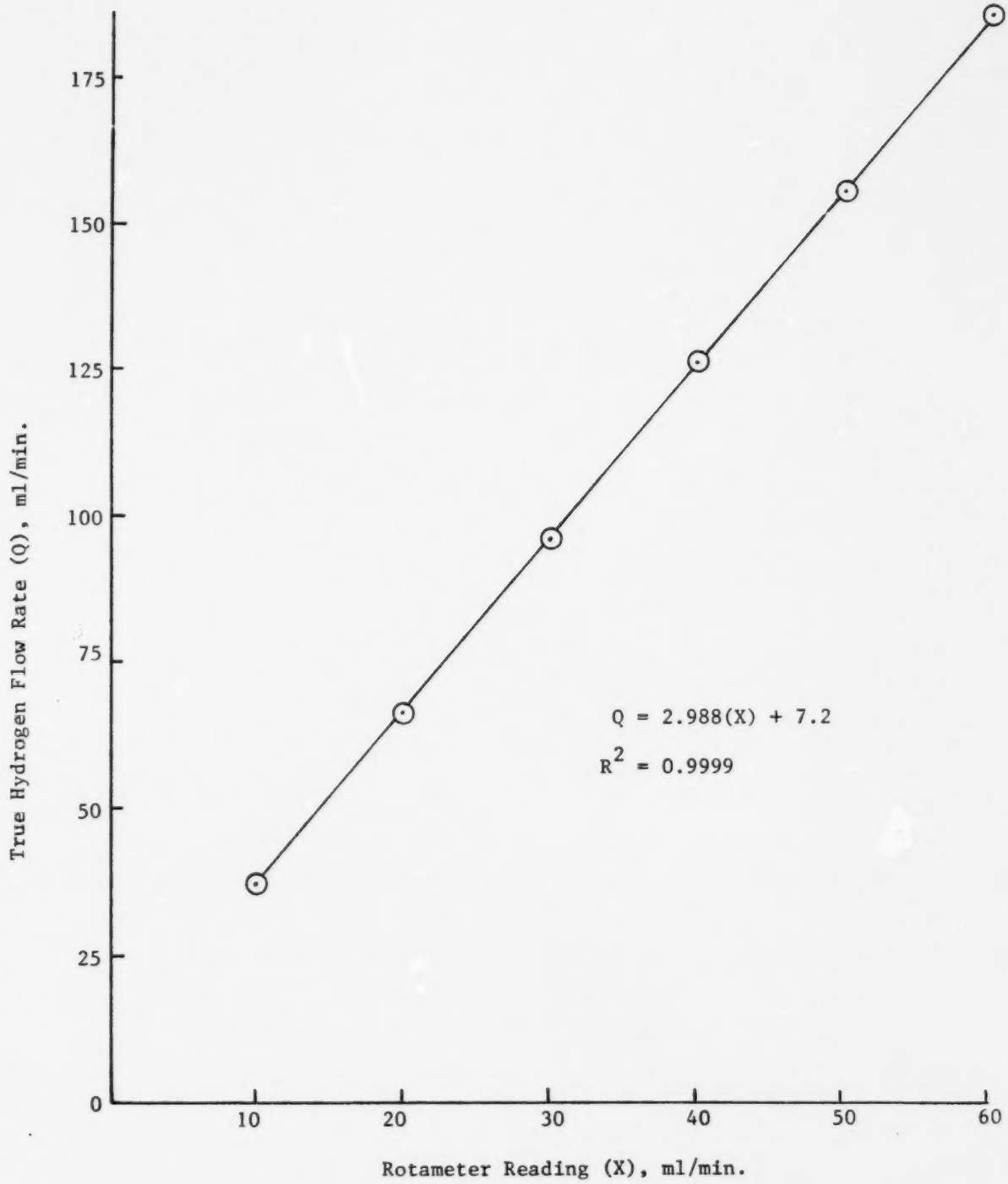


Figure 8 Calibration curve for hydrogen to the FID.
(For H_2 at T = 23°C, P = 765 mm Hg)

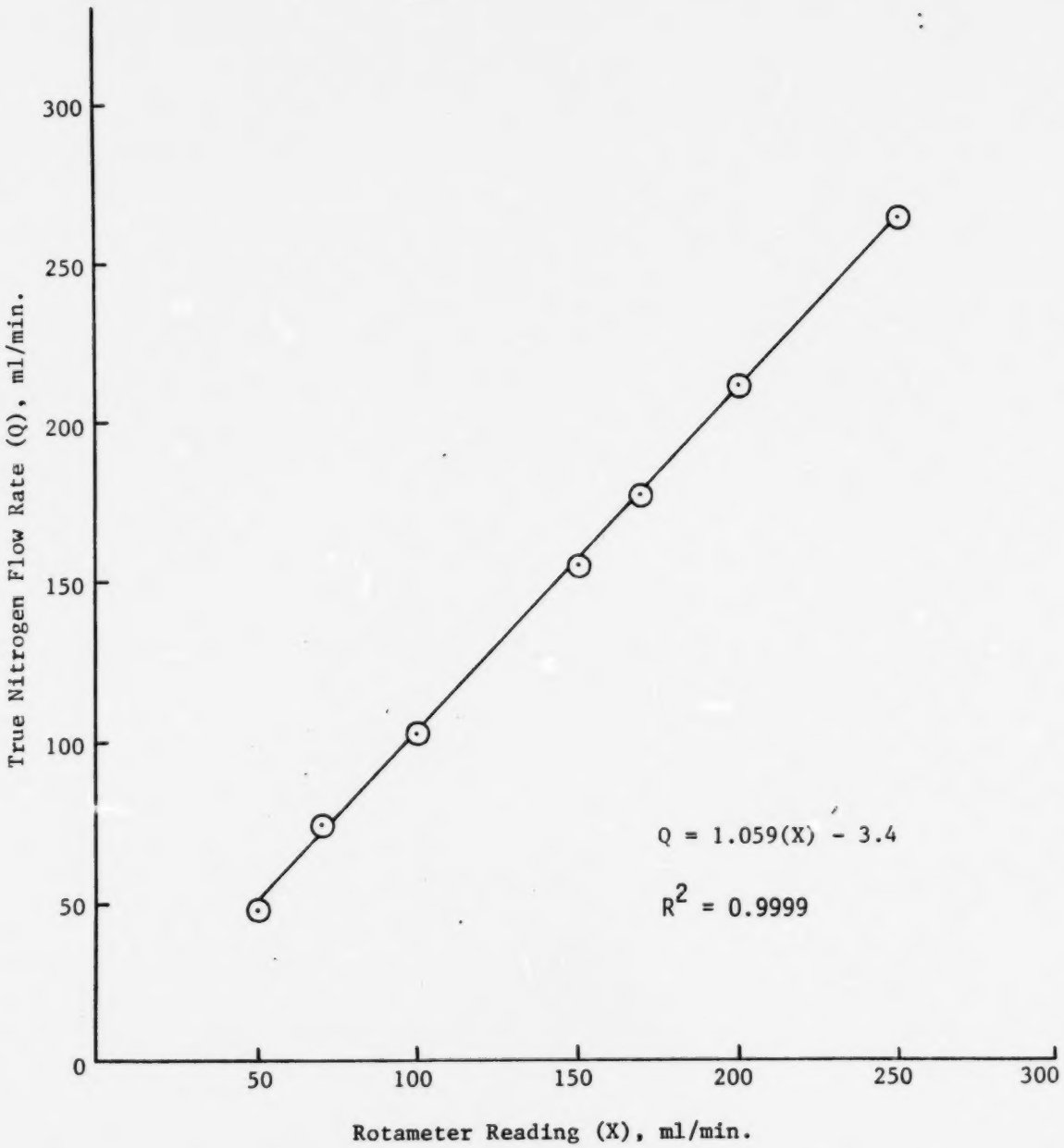


Figure 9 Calibration curve for instrument nitrogen.
(For N_2 at T = 26°C, P = 770 mm Hg)

Main air rotameter--The main air rotameter was calibrated using the previously calibrated Rockwell S-200 dry gas meter. The air supply was house air which was passed first through the filter package. The the air split into two streams; the main one of which passed through a flow control valve and through the larger rotameter. At the exit of the rotameter, the temperature and pressure were measured. The air stream then passed through the dry gas meter and exited to the atmosphere. Several different flow rates were tested, each at least three times. The calibration data were plotted and fit by a linear least squares technique. The fit was excellent as shown in Figure 10. The calibration equation and coefficients are shown on the figure.

Solvent carrier air--The other branch of the main air supply stream mentioned above was routed through a similar rotameter system (control valve, rotameter, etc.). This air stream, which was to be used as the solvent carrier stream) was then routed through the dry gas meter and exited to the atmosphere. Several flow rates were tested, each at least three times. The calibration data were plotted and fit by a linear least squares technique. The fit was excellent as shown in Figure 11. The calibration equation and coefficients are shown on the figure.

Additional air rotameters--Two identical air rotameters (both smaller than the two main rotameters) were purchased for this project. The additional solvent air rotameters were calibrated using the previously calibrated wet test meter. The air supply was house air which was passed first through the filter package, then through a flow control valve and through the rotameter. At the exit of the rotameter, the temperature and pressure were measured. The air stream then passed through a saturator, then the wet test meter and exited to the atmosphere. Several different flow rates were tested, each at least three times. The calibration data were plotted and fit by a linear least squares technique. The fit was excellent as shown in Figure 12. The calibration equation and coefficients are shown on the figure.

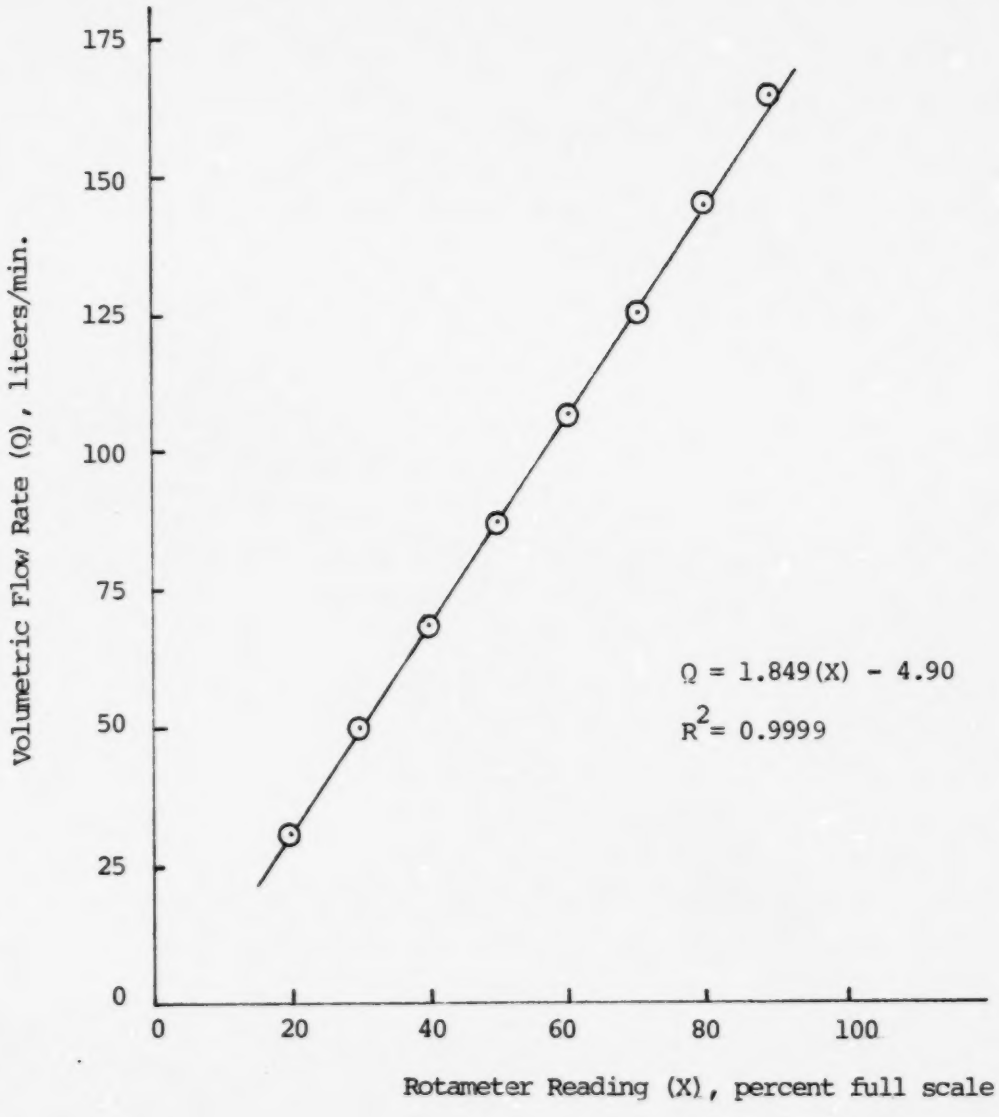


Figure 10 Calibration Curve for Main Air Rotameter
(For air at T = 23°C, P = 0.9 psig)

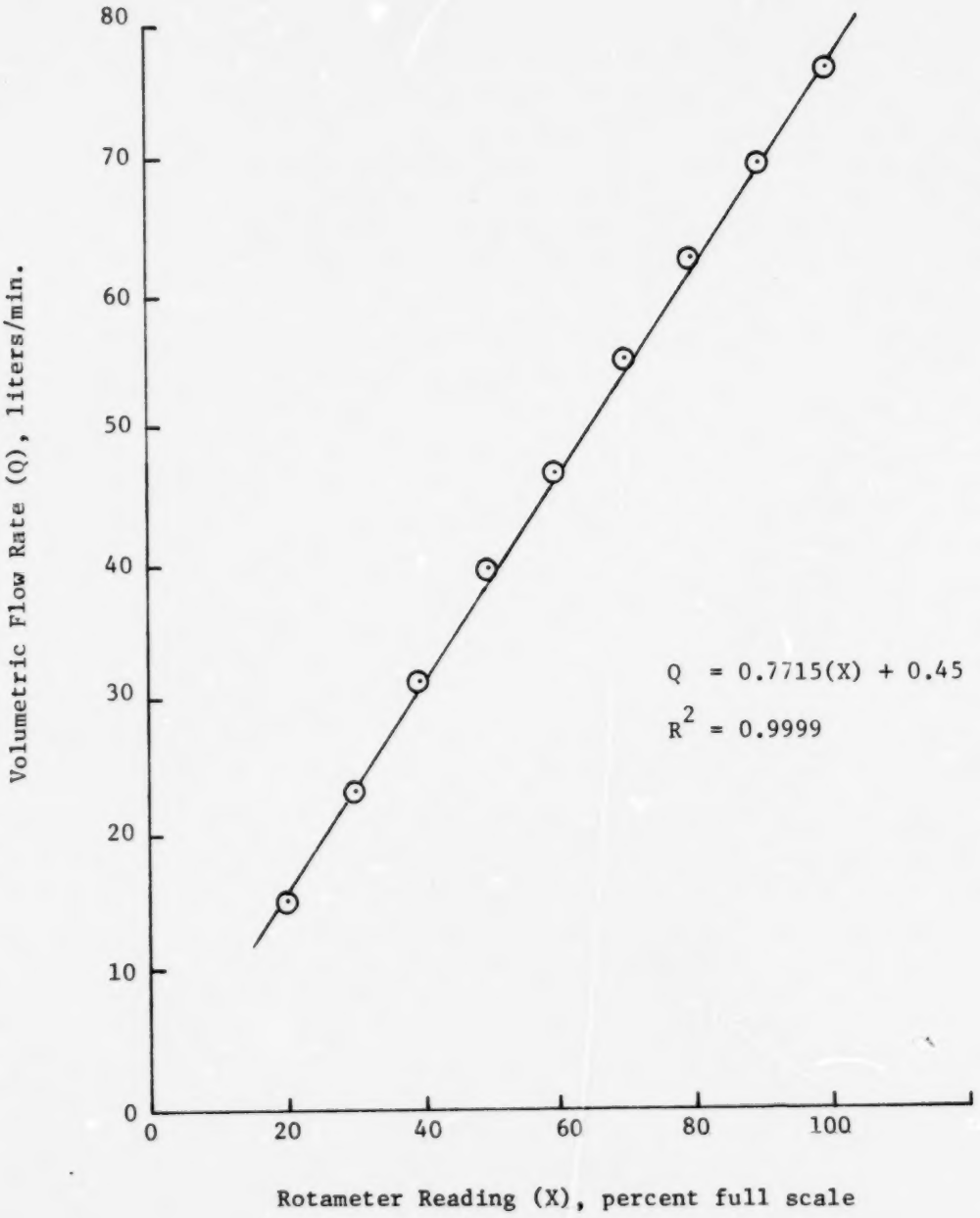


Figure 11 Calibration Curve for Solvent-Carrier Air Rotameter (For air at T = 22°C, P = 1.00 atm)

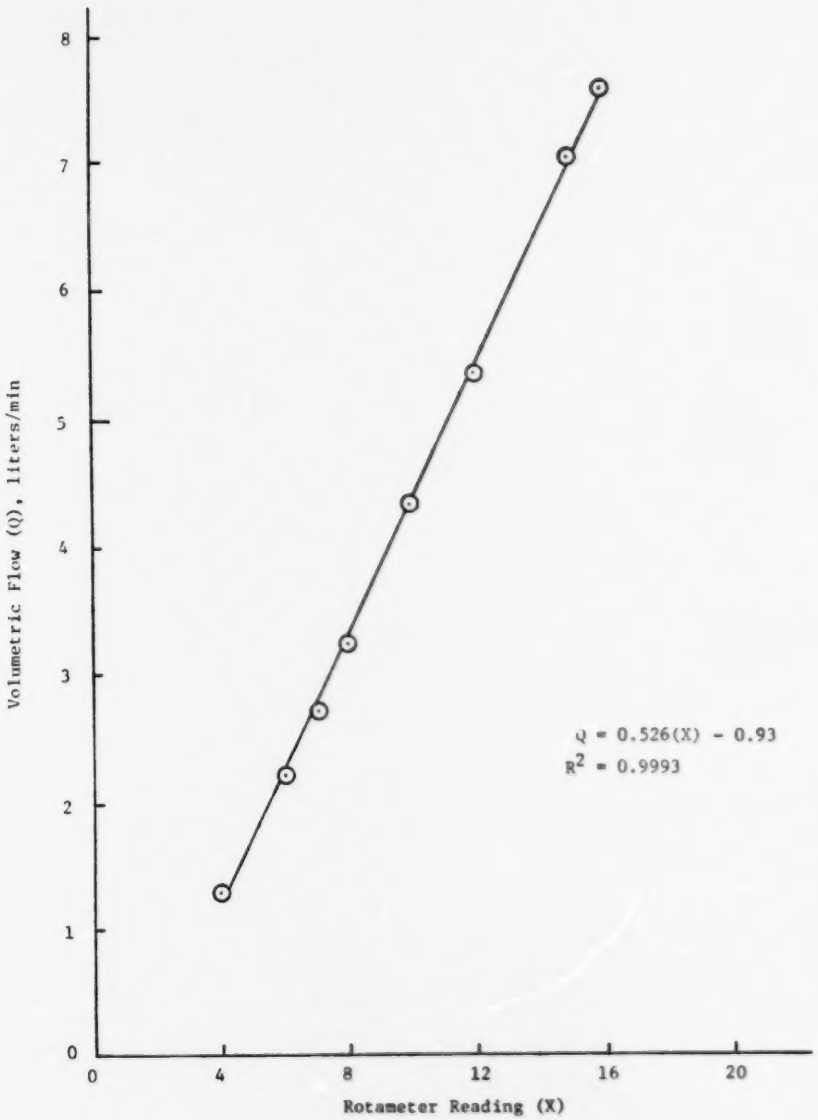


Figure 12 Calibration Curve for Solvent - Carrier Air Rotameter (Tube No. FP-1/4-16-G-5/84; for Air at 22 °C, P = 1.00 atm)

Calibration of Analytical Instruments--

CO Analyzer--A new, state-of-the-art CO analyzer was purchased (by the College of Engineering, using separate funds) for this project. The analyzer is a Thermoelectron Model 48 with sensitivity to 0.2 ppm CO in air. It is specially equipped with a programmable chip to linearize the NDIR response over a number of ranges up to 1000 ppm. In order to properly calibrate the instrument, we purchased four cylinders of CO in air from Scott Specialty Gases, a supplier of certified standards. Each cylinder was analyzed by Scott and certified to be within 2 percent accuracy. The concentrations supplied were 10.5, 49.3, 100.2, and 998 ppm.

Initially, the highest concentration certified gas (998 ppm) was used to span the instrument, following which the three other gases were tested. The results showed about 4 percent error as listed in Table 4. Because the expected concentrations of CO from the SUNKISS were less than 100 ppm, the unit was re-calibrated using the 100.2 ppm gas as the standard. The instrument results were closer to the actual gas concentrations over this smaller range as shown also in Table 4.

TABLE 4

CO ANALYZER CALIBRATION CHECKS

Actual	Instrument (1)	Instrument (2)
10.5	10.0	10.2
49.3	47.1	48.6
100.2	96.0	100.2
998	999	---

(1) Thermoelectron analyzer spanned using the 998 ppm gas as a standard.

(2) Thermoelectron analyzer spanned using the 100.2 ppm gas as a standard.

Gas Chromatograph--The gas chromatograph (Fisher model 2400) was calibrated for hexane, and the other solvents used in this study. The calibration basically involved establishing several known concentrations of hexane in air by mixing a stream of dry air with a stream of air saturated (at 0°C) with solvent. By adjusting the flow rates of each stream, various concentration mixtures were produced. As pointed out previously, the accuracy of this method is limited by the accuracy of the air flow rates. However, this method is precise (repeatable) during one run, and from run to run. The variation of the calibration from one day to the next was less than 10 percent even at the 200 ppm range. Thus the main purpose of the testing, to assess the percentage VOC destruction efficiency of the SUNKISS, was not compromised.

Several problems were encountered with the GC. It was found that the response of the instrument was quite dependent on the pressure of the carrier gas (nitrogen) into the GC. Great care was taken to ensure that all measurements were made at a constant inlet nitrogen pressure of 20 psi. Also, the oven temperature controller of the GC was intermittently unstable and affected the results. Manual adjustments were made periodically to compensate for this effect, and later a factory representative repairman was called out to solve this annoying problem. Considerable care was taken to ensure that all readings were taken at the same oven temperature.

The hexane calibration data for the GC are shown in Figure 13. Each data point represents the average of three trials on three different days. Each trial agreed with the others to within ±7 percent. As can be seen, the results are quite linear over the calibration range.

Thermocouples--Each of the thermocouples was calibrated in conjunction with the digital temperature indicator. Each thermocouple was immersed in an ice-water bath and then later in boiling water. For properly operating thermocouples, the temperatures read either 0 or 100°C (±0.5°C). One faulty thermocouple was discovered by this simple check.

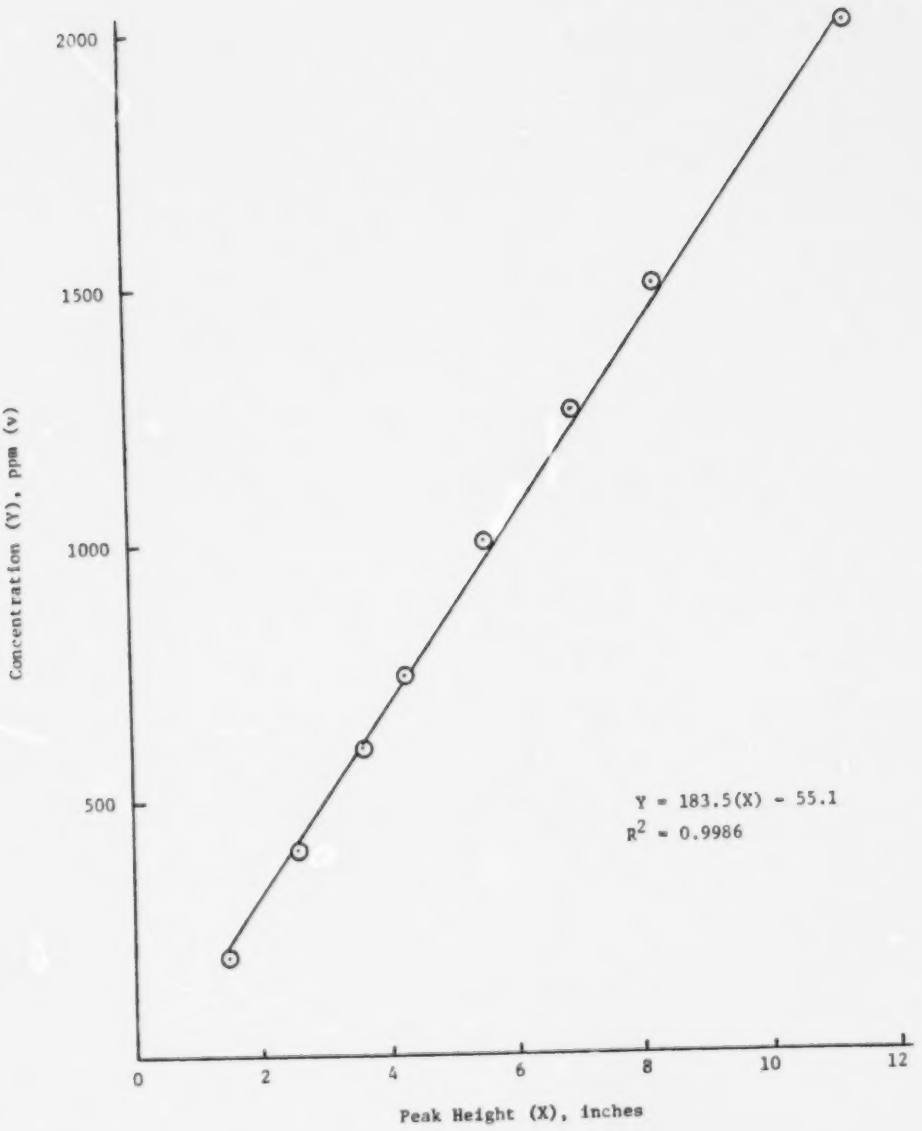


Figure 13 Calibration Curve for Gas Chromatograph, Hexane in Air

SECTION 5

RESULTS AND DISCUSSION

CHAMBER MIXING TEST

Initial tests were conducted to test the degree of mixing in the chamber using the SUNKISS unit fan (about 1.7 m^3/min capacity) to provide the mixing. During these tests, the catalyst heating mode was off. The time response of the chamber outlet concentration to a step input in the inlet VOC concentration indicated very good mixing. Good mixing was confirmed by the nearly identical values of VOC concentrations at all three sampling points (outlet, center-back, and lower-far-corner) at all times during the test.

However, during the initial testing of the SUNKISS unit in the heating mode, some question arose regarding the complete mixing of the inlet air in the area of the SUNKISS catalyst surface. Two additional fans were installed in the chamber to enhance the mixing. The two fans had capacities of about 4 m^3/min and 6 m^3/min respectively. The larger fan was placed directly across the chamber from the SUNKISS Unit at the fresh air entrance and was positioned to blow directly towards the unit. These fans were tested sequentially. The mixing characteristics were essentially the same as previously observed.

With the larger fan and the SUNKISS fan operating, a fresh air flow of about 165 l/min was introduced into the chamber. At time = 0, an additional air stream (saturated with hexane) was mixed with the first giving a total

air flow of 170 l/min and an inlet VOC concentration of 1000 ppm. The outlet and two interior points of the chamber were sampled every 60 seconds until they reached steady state (inlet concentration) values. This test was repeated three times and gave essentially identical results each time, either with a step increase or decrease in inlet VOC.

Figure 14 is a reproduction of the actual chromatographic trace from one of the mixing tests. The response observed in Figure 14 is nearly identical to that of a "text-book" first order system with a time constant of 5.75 minutes. A completely mixed tank is theoretically a first order system with a time constant equal to the volume of the tank divided by the volumetric flow rate. Since a 1.0 m^3 tank with a 170 l/min air flow rate (our system) has a theoretical time constant of 5.88 minutes, it was concluded that our chamber behaved essentially like an ideal, completely mixed tank. When a reaction occurs in a completely mixed tank it is often referred to as a continuously stirred tank reactor (CSTR), and this nomenclature (CSTR) will be used hereafter.

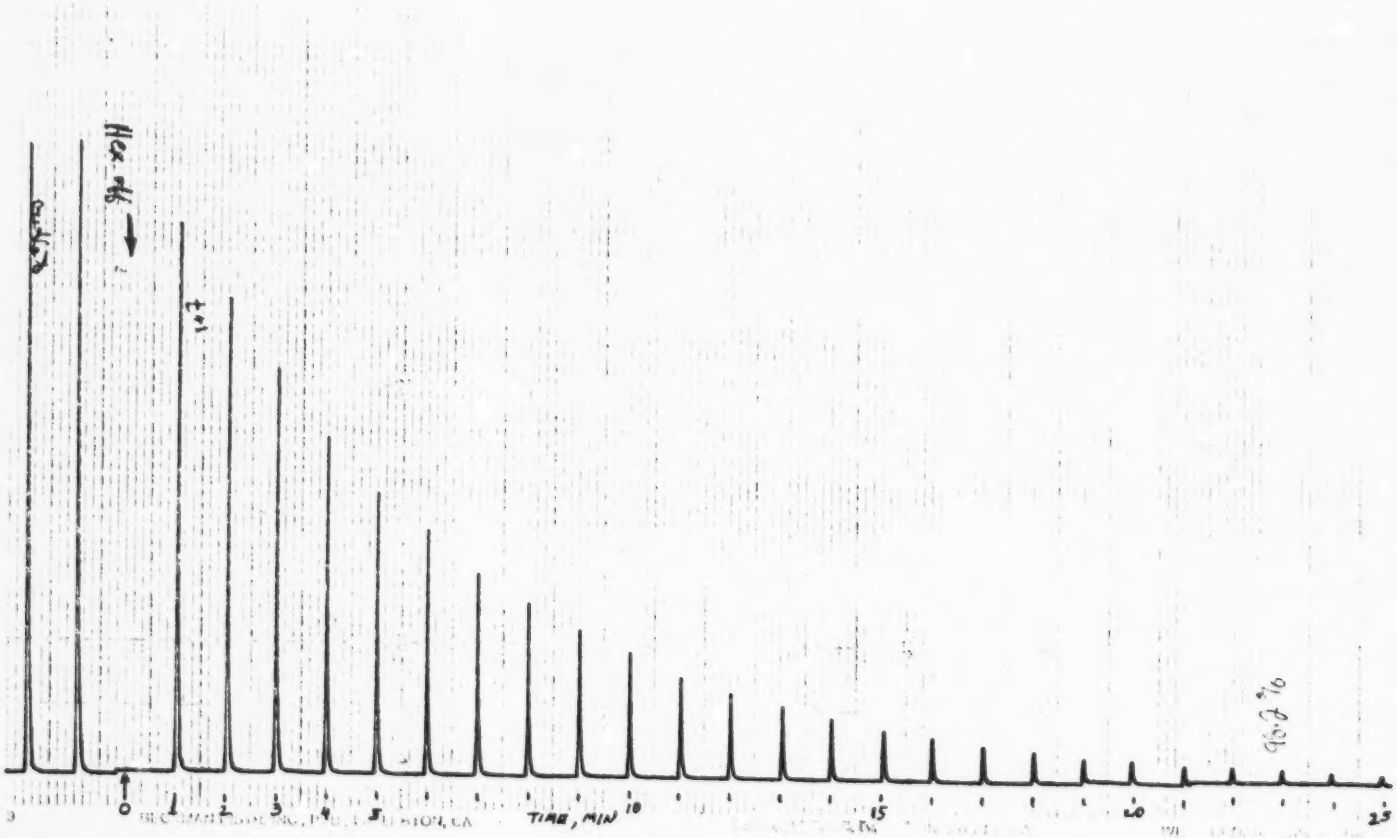


Figure 14 Mixing Test on Chamber; Time Response of Hexane in Chamber Outlet to Step Decrease in Chamber Inlet.

INITIAL OPERATING TESTS

Initial tests of the SUNKISS unit were performed with the SUNKISS unit on with only fresh air (no VOC) entering the chamber. A VOC response was observed on the GC, which implied that some uncombusted propane fuel might be escaping into the chamber. Introduction of some hexane into the inlet air and observation of two separate peaks on the GC confirmed that propane gas was indeed entering the chamber. Disappearance of one peak when the propane fuel valve was closed further proved that one peak was propane. Discussions with technical personnel at SUNKISS indicated that our air flow rate might be too low. But the air flow rate (6 cfm) was higher than the recommended operating range in several of the brochures (4 cfm). However, it is possible that air flow rates in commercial ovens are even higher than 6 cfm per SUNKISS unit. Recognition of the problem of propane non-combustion led to more detailed testing during the solvent destruction efficiency tests. In later tests, we calculated the percent propane combustion to be in the 98% to 99.8% range depending on total air flow rate. Also, modifications (thicker pad and higher fuel pressure) of the SUNKISS device during the latter part of this research partially alleviated this problem of propane non-combustion. Quantitative propane results will be presented in detail later in this Section.

EFFECT OF SOLVENT CONCENTRATION

Several tests were conducted at 170 l/min (6 cfm) air flow but at different inlet concentrations of hexane in air. Basically, chamber inlet and outlet (and some interior points) concentrations were measured to determine the percentage destruction efficiency for the SUNKISS unit.

The goal was to determine the VOC destruction efficiency of the SUNKISS device. For a constant total molar flow of gas through a CSTR, the VOC destruction efficiency (on a mass or molar basis) can be calculated as

follows

$$E = \frac{C_o - C_e}{C_o} = 1 - \frac{C_e}{C_o} \qquad (1)$$

where E = fractional destruction efficiency

C_o = inlet VOC concentration, ppm

C_e = outlet VOC concentration, ppm

When the total molar flow rate out of the chamber is not equal to the inflow rate of solvent laden air (which occurs when the fuel gas plus a second stream of air enters the chamber), then the VOC destruction efficiency must be calculated as follows

$$E = \frac{n_o C_o - n_e C_e}{n_o C_o} = 1 - \frac{n_e C_e}{n_o C_o} \qquad (2)$$

where: n_o = inlet molar flow rate of stream of air with VOC

n_e = total molar flow rate of exhaust gases

The second equation properly accounts for the dilution effect - that is, the fact the VOC concentrations in the outlet stream will be somewhat lower than in the inlet due solely to dilution by the addition of other gases.

Even though the oxidation of the VOC produces more moles of gas than it consumes (13 moles produced vs. 10.5 consumed for the complete oxidation of hexane), because the VOC was always less than about 0.2% (2000 ppm), the molar expansion due to VOC combustion was neglected. It was determined from data supplied by the manufacturer that the propane injection rate was approximately 0.087 gmole/min. Furthermore, based on data from the manufacturer, we calculated that the ambient air entrained by inlet jet of the fuel (the primary air) was approximately 0.133 gmole/min. Complete propane combustion produces 7 moles of gases for 6 consumed. Thus, the total

molar flow of gases exiting the chamber was equal to the sum of the moles of solvent laden air flowing in plus 7/6 times the propane flow plus the entrained ambient air flow. In other words, molar flow rate out was equal to moles of solvent laden air in plus 0.23 gmoles/min. At low inlet air flow rates, this additional 0.23 gmoles/min was a significant fraction of the total flow rate.

Quite a few individual solvent destruction tests were accomplished using hexane in air. All replications of individual tests were quite reproducible. Certain concentrations of hexane-in-air and certain air flow rates into the chamber were replicated as many as five or six times. The destruction efficiency for each test never varied more than two percentage points from the mean. The results are shown in Table 5 and Figure 15.

TABLE 5

Effect of Hexane Concentration on Destruction Efficiency

Measured Hexane Concentrations, ppm		Total Molar Flow Rate of Gas, gmole/min		
Inlet	Outlet	Inlet	Outlet	Destruction Efficiency, %
165	128	7.07	7.30	19.9
642	496	7.07	7.30	20.2
991	752	7.07	7.30	21.6
1560	1174	7.07	7.30	22.2
2184	1652	7.07	7.30	21.9
			Average	21.2

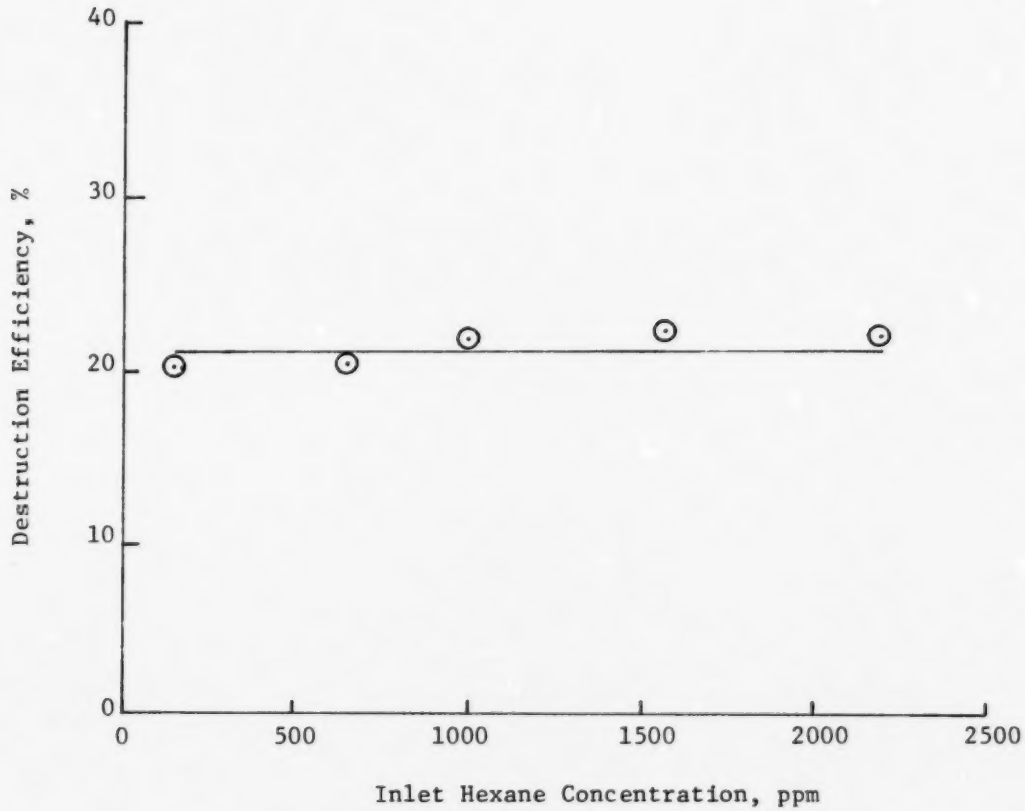


Figure 15 Hexane Destruction Efficiency vs. Inlet Hexane Concentration

EFFECT OF CHAMBER RESIDENCE TIME

After it was shown that destruction efficiency was essentially independent of inlet hexane concentration, the effect of inlet air flow rate was investigated. At each flow rate only two or three concentrations were used. At the lowest flow rates, the time constant of the chamber (chamber volume divided by inlet air volumetric flow rate) became relatively large. Since we waited at least four time constants for the system to come to steady state for each new test, the low air flow rate tests were lengthy. At 2 cfm, only 1000 ppm concentration was used, but three replications were made. The relationship between destruction efficiency and inlet air flow rate is shown in Figure 16.

For a fixed volume chamber, the volumetric air flow rate into the chamber is related to the inverse of the average residence time. The average residence time in a CSTR is actually best calculated by the volume of the chamber divided by the exhaust gas rate. In our experiments, the exhaust gas volumetric flow rate was higher than the measured air inflow rate due to the fuel and primary air inflow, and due to the volume expansion of the gas in the chamber due to increased temperature.

The ideal gas law was used to calculate the outlet exhaust volumetric flow as shown in equation (3).

$$Q_e = n_e \; R \; T_e/P_e \qquad (3)$$

where: Q_e = exhaust gas flow rate, m^3/min

R = ideal gas law constant, $8.205\ (10)^{-5}\ m^3$ atm/gmole °K

T_e = exhaust gas temperature, °K

P_e = exhaust gas pressure, atm

Since T_e was always 75-85°C, and P_e was essentially atmospheric pressure, equation (3) was used as follows:

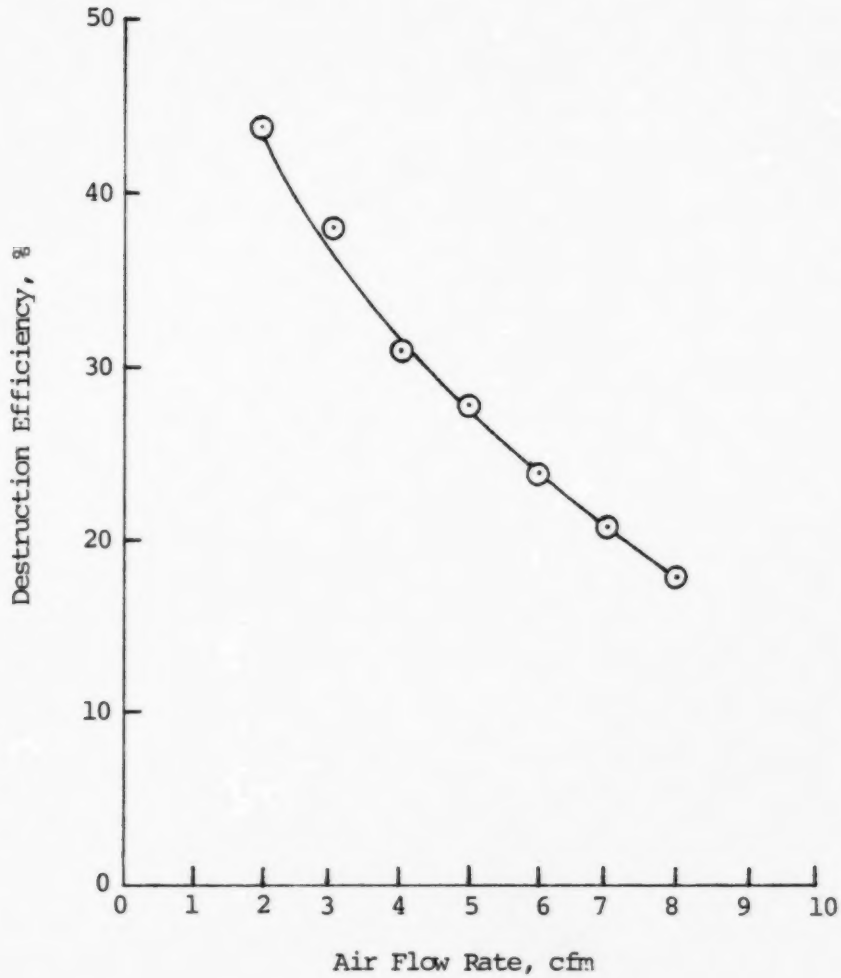


Figure 16 Hexane Destruction Efficiency for SUNKISS Device vs. Air Inflow Rate.

$$Q_e = k\, n_e \qquad (4)$$

where: $k = RT_e/P_e$ (k varies between 0.0286 and 0.0294)

The average gas residence time in the chamber (assuming a 1.0 m^3 volume) was calculated as

$$t_R = 1.0/Q_e \qquad (5)$$

where: t_R = average residence time, minutes.

As might be expected, the residence time in the chamber is a key parameter in determining the destruction efficiency.

Hexane Tests

Tests were run to assess destruction efficiency vs. residence time for hexane, MEK, and toluene. The hexane data are plotted vs. residence time in Figure 17 and are tabulated in Table 6.

TABLE 6

Effect of Gas Residence Time on Hexane Destruction Efficiency

Inlet Air Flow		Outlet Gas Flow		Average Residence	Destruction
cfm	gmole/min	gmole/min	m^3/min	Time, min	Efficiency,%
2	2.35	2.58	0.075	13.3	44
3	3.54	3.77	0.109	9.2	38
4	4.70	4.93	0.143	7.0	31
5	5.91	6.14	0.178	5.6	28
6	7.07	7.30	0.21	4.8	24
7	8.24	8.47	0.25	4.0	21
8	9.44	9.67	0.28	3.6	18

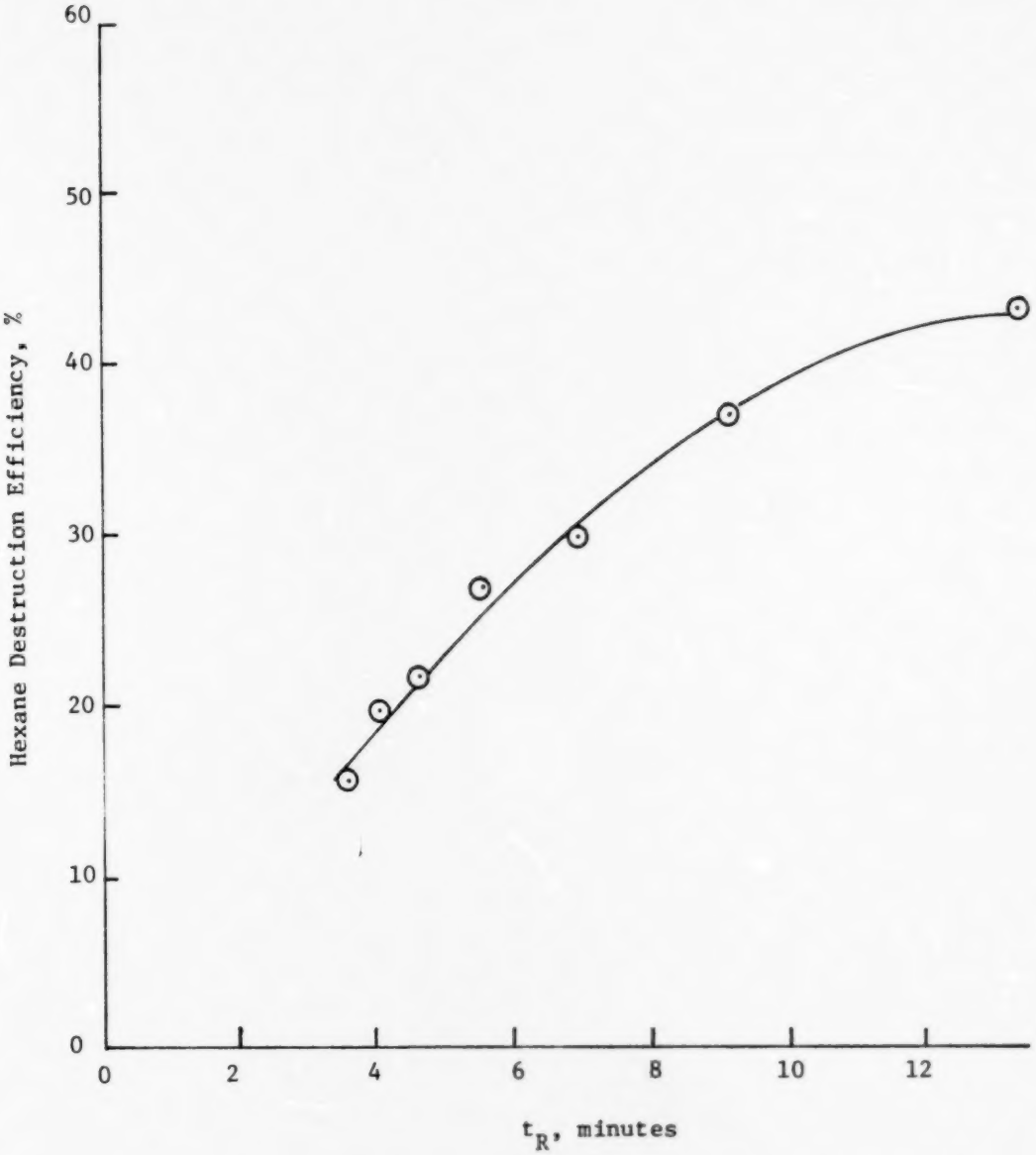


Figure 17 Hexane Destruction Efficiency vs. Gas Residence Time

As mentioned previously, during the initial hexane tests, it was discovered that a small amount of propane fuel escaped into the chamber uncombusted. Furthermore, a small amount of CO was generated during the normal operation of the device. Both the residual propane concentrations and the CO concentrations in the chamber were shown to be functions of the inlet air flow rate as shown in Figure 18.

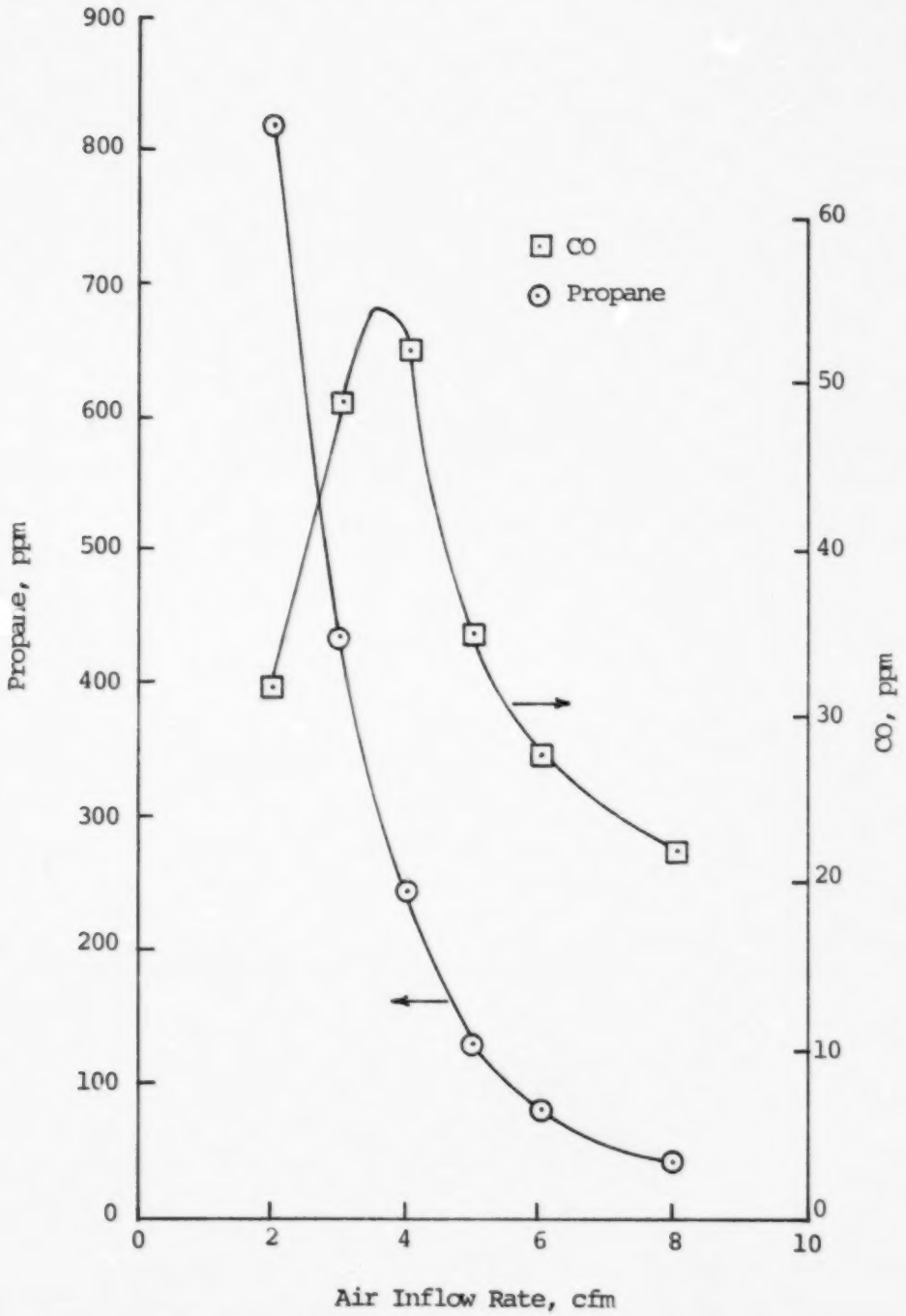


Figure 18 Propane and CO in Exhaust Gases, SUNKISS Device Operating on 1000 ppm Hexane in Air.

EFFECT OF SOLVENT TYPE

In addition to hexane, two other common paint solvents were tested: methyl-ethyl-ketone (MEK) and toluene.

MEK Tests

After completion of all the hexane tests, MEK was placed into the saturation system and the tests were repeated for MEK. The data were more troublesome to obtain; MEK did not respond as well in the GC. Nevertheless, data reproducibility was still reasonably good. Furthermore, when the MEK data were compared with the hexane data, the results were very encouraging.

In essence, the MEK destruction efficiencies nearly duplicated those observed with hexane. The MEK data trended a slight bit lower than hexane and showed a slight bit more scatter, but the same essential behavior was evidenced.

Toluene Tests

As part of a planned attempt to more closely simulate conditions in a real oven, a painted (black) metal plate was placed inside the test chamber during the toluene tests. The plate measured approximately 40 cm by 65 cm, and was placed normal to the IR from the catalyst pad about 40 cm from the device. The purpose of the plate was to simulate a painted part being cured. It was suggested by the manufacturer that as the plate heated (due to absorption of IR) the air temperature in the chamber would increase. Due to increased front-of-pad temperatures, then, the solvent destruction efficiency of the SUNKISS unit would increase.

The results of the toluene tests at first seemed very encouraging. Although the chamber air temperatures increased only about 5°C above those previously observed (without the plate), the efficiencies for toluene destruction were about 14 to 18 percentage points higher than those for

hexane or MEK at the three flow rates tested. That is, at inlet air rates of 2, 5, and 8 cfm, the destruction efficiencies were 63%, 43%, and 32% for toluene, whereas hexane efficiencies of 44%, 28%, and 18%, respectively, were previously observed.

However, we then removed the painted plate and observed toluene destruction efficiencies of 38% at 5 cfm and 30% at 8 cfm. These efficiencies (without the plate) were 2-4 percentage points below those observed with the plate. Thus, the plate apparently was not the main reason for the increased destruction efficiency of the SUNKISS unit operating with toluene. Our preliminary conclusion was that toluene was simply a more reactive gas than hexane.

PAINTED OBJECT TESTS

Painted Plate Effects

To further test our conclusion that the painted plate was not significantly altering the SUNKISS unit efficiency, and to ensure that operator differences were not significant, we re-ran hexane tests at inlet air flow rates of 5 and 8 cfm with and without the painted plate. Also, we ran more toluene tests. The results confirmed our conclusion and further demonstrated that the painted plate enhanced destruction efficiencies only slightly (on average, about 2%). All pertinent results are shown in Table 7; each reported efficiency is an average of three separate tests, and none of the individual tests varied by more than 2 percentage points from the average. The toluene data without the plate are shown in Figure 19 in comparison with the hexane and MEK data.

TABLE 7

SUNKISS Unit Performance With and Without Painted Plate

Air Inlet Flow Rate		Destruction Efficiency %			
		Toluene		Hexane	
cfm	lpm	with	without*	with	without
2	56.6	63	59	--	--
3.5	100	43	43	--	--
5	142	42	38	30	28
8	227	32	30	20	18

*with or without painted plate

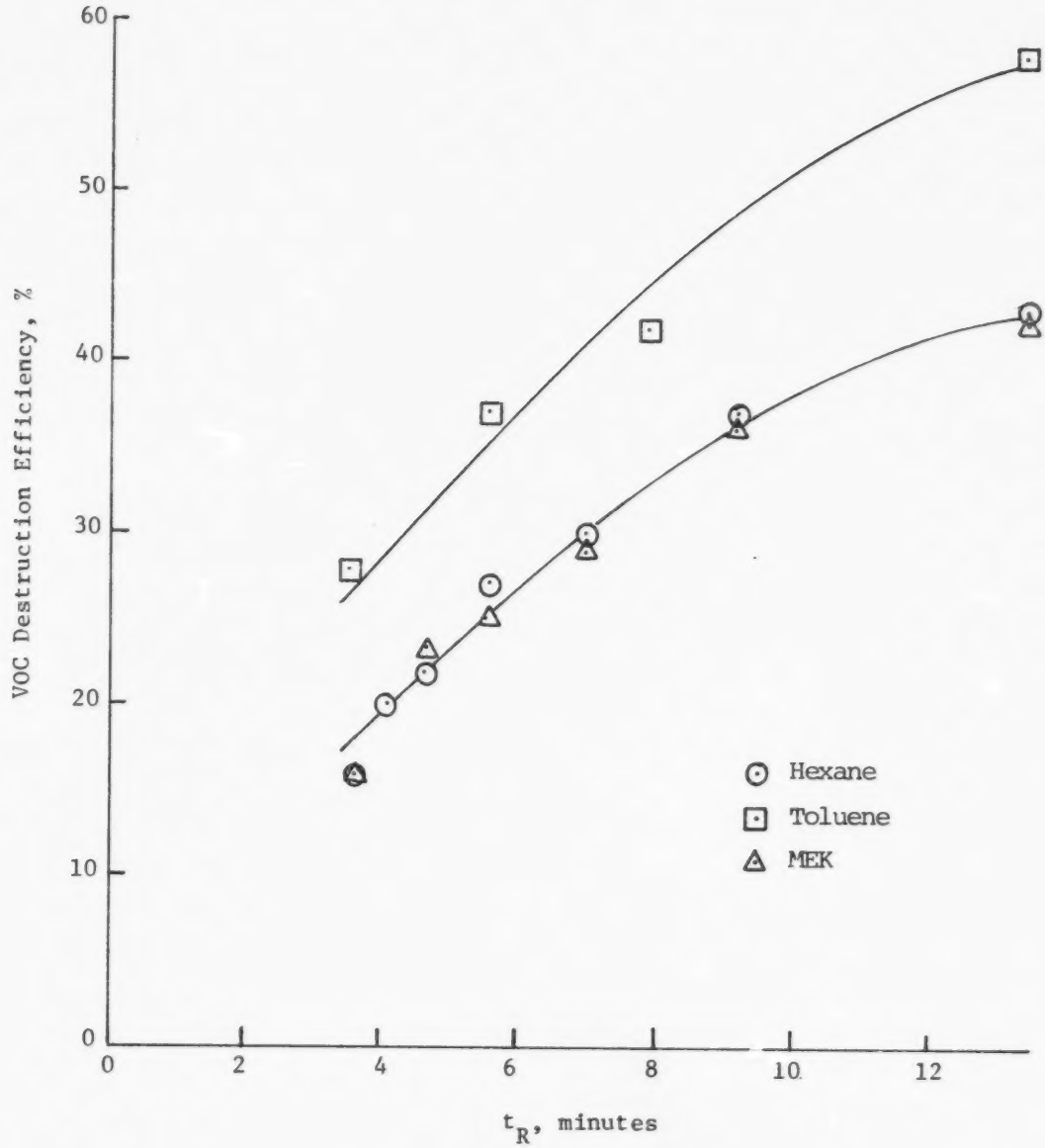


Figure 19 VOC Destruction Efficiency vs. Gas Residence Time

A different painted plate test was conducted to assess the absorbance of IR by a painted surface. Two identical thin steel plates, each 19.5 cm x 66 cm x 1.5 mm were used in these tests. One was painted glossy black and the other was left unpainted. Holes were drilled approximately 8 cm from the top for a bolt and washer assembly designed to hold a thermocouple snug to the surface of the plate. The bolt head and washer were painted for the painted plate and unpainted on the unpainted plate. Care was taken to position and orient the plates identically about 25 cm in front of the SUNKISS catalytic head. The plates were side-by-side with about a 3 cm gap between the edges.

Three tests were run to assess the IR absorbance by the painted plate. Air (without any solvent) was started through the chamber at 8, 5, or 3 cfm (226, 142, or 85 liters per minute). At time 0, the SUNKISS unit was started. The temperature of both plates increased, but the painted plate temperature increased faster and to a greater extent. The detailed data are presented for the low and high flow rates in Figures 20 and 21. As can be seen, the steady-state painted plate temperature was about 40°C above the unpainted plate temperature.

Painted Dispersion Cone Tests

A dispersion cone was constructed to release the solvent-in-air mixture closer to the SUNKISS unit. The face of the dispersion cone was circular with a diameter of approximately 35 cm. The face was painted black and had numerous 1/8-inch holes drilled in it. The hole area was approximately 5 percent of the face area. A schematic diagram of the dispersion cone and its placement in the chamber is presented in Figure 22.

Tests were conducted (using hexane) with and without the external chamber mixing fan at two air flow rates. Each test was repeated three times and the percentage destruction efficiencies were averaged. The results are presented in Table 8.

TABLE 8

Effect of Dispersion Cone on SUNKISS Unit Performance

Inlet Air Flow Rate, cfm	Mixing Fan Status	Hexane Destruction Efficiency, %	Representative Efficiency without Cone, %
5	On	26	
5	Off	27	28
8	On	21	18
8	Off	19	

As can be seen from Table 8, within the limits of precision for this work, there was no difference between the results achieved with the chamber external mixing fan on or off. Furthermore, the destruction efficiencies achieved with the dispersion cone were about the same as those observed previously without the cone at the same air flow rates.

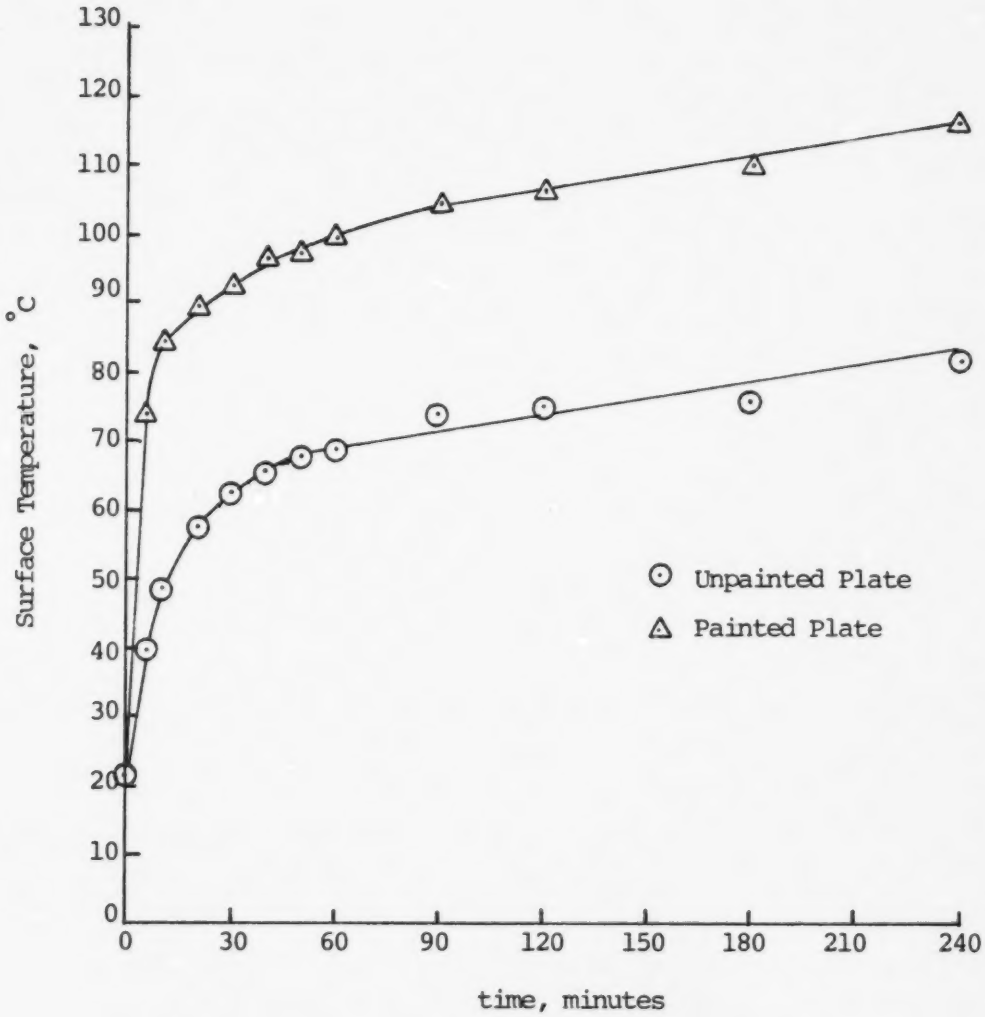


Figure 20 Temperature Response of Painted and Unpainted Plate after SUNKISS Start-Up (Air Inflow = 3 cfm).

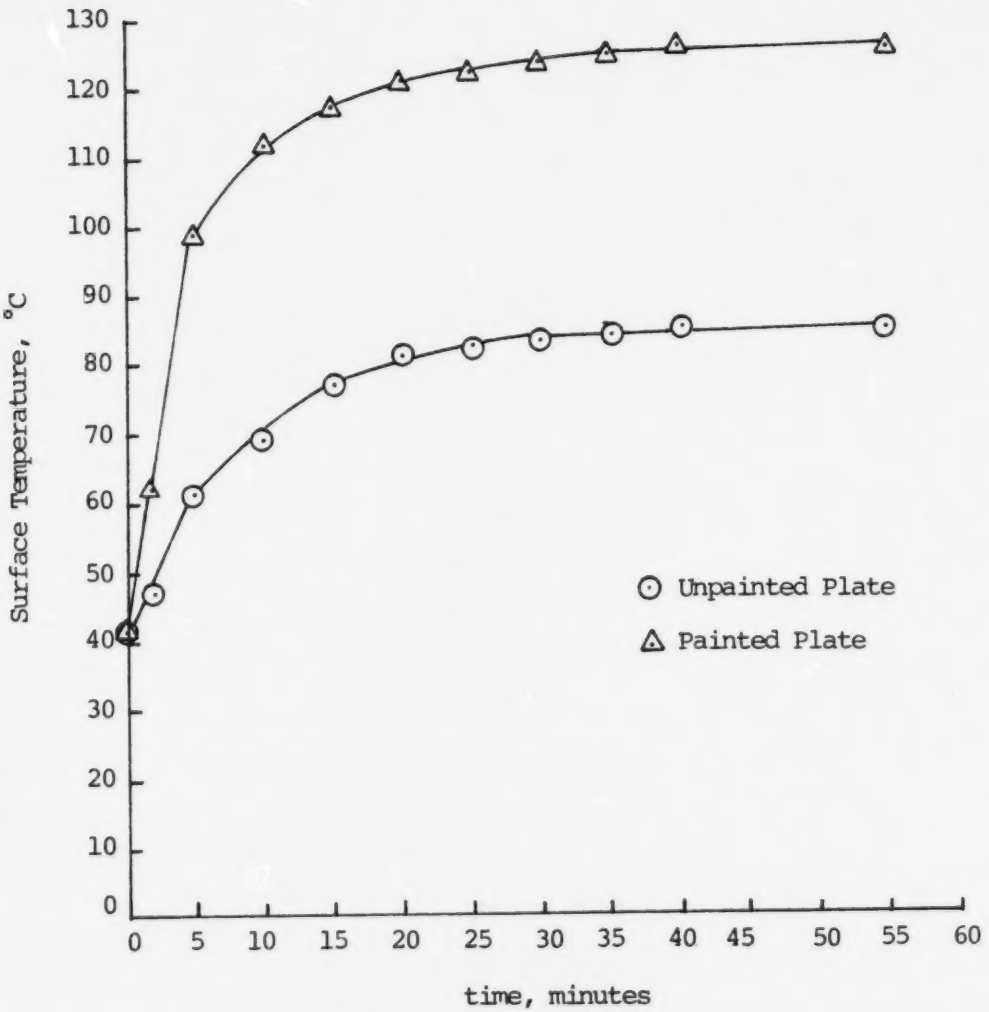
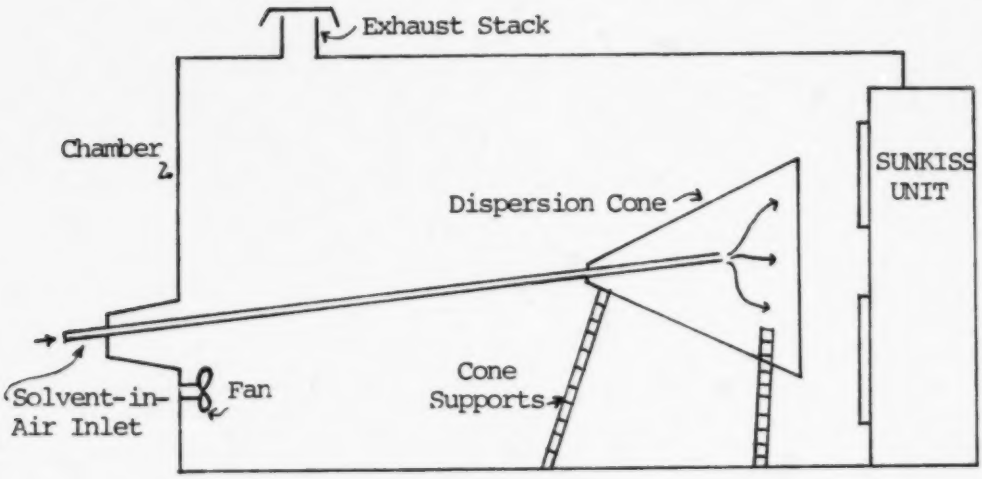


Figure 21 Temperature Response of Painted and Unpainted Plate after SUNKISS Start-Up (Air Inflow = 8 cfm).

Side View



Front View

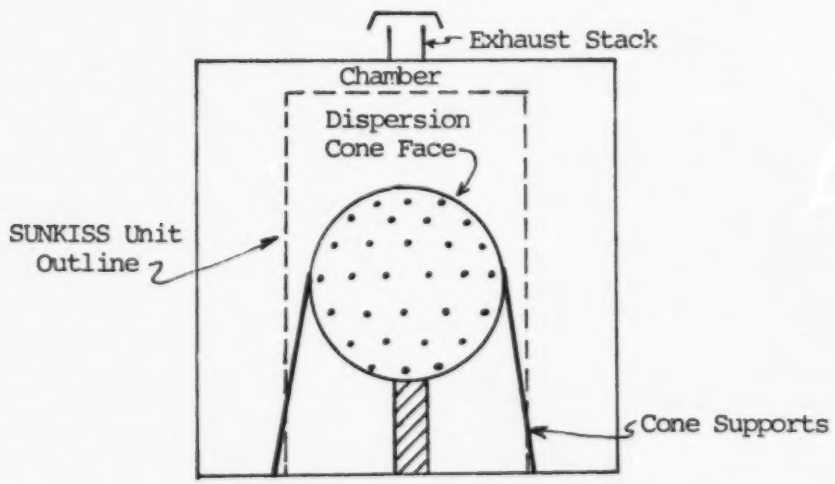


Figure 22 Schematic Diagram of Cone Emplaced in Chamber.

EFFECT OF SUNKISS DEVICE MODIFICATIONS

During the course of this research project, the manufacturer introduced modifications to the basic device that were intended to increase solvent destruction efficiency and to decrease residual (unburned) propane concentrations. The modifications were basically (1) smaller fuel jets with an increased fuel supply pressure, and (2) a thicker catalyst pad with more catalyst surface area. Each of these modifications was tested in the UCF experimental test system.

Higher Fuel Pressure

Leaving the old catalyst pad in place,the old fuel injection orifice was replaced by the new smaller one. The propane fuel pressure was increased from 11 inches of water (2.8 kPa) to 2 psig (14 kPa). Hexane was used as the solvent and several air flow rates were tested (all at an inlet hexane concentration of 1000 ppm). Three replications were made at each of six flow rates and outlet hexane concentrations were measured. Also, outlet propane and CO concentrations were measured at each inlet air flow rate.

Thicker Catalyst Pad

The old catalyst pad was replaced by the new thicker catalyst pad and the hexane tests described above were repeated (using the 2 psig fuel pressure).

The results of the above two sets of test initially indicated an apparent slight (but not negligible) improvement in VOC destruction. The higher fuel pressure injection system with the old thin pad had resulted in lower hexane outlet concentrations compared with the initial hexane results. Use of the thicker catalyst pad along with a higher fuel pressure apparently further increased destruction efficiencies because outlet hexane concentrations were reduced even further than those achieved with the old pad. In addition, propane non-combustion with the new system (new pad-new jets)

apparently was reduced considerably at all flow rates compared with that observed with the old system. CO concentrations were lower at the high air flow rates but higher at the low air flow rates. The propane and CO results are shown in Figures 23 and 24 respectively.

The word "apparently" was used in the previous discussion because there is an increase in dilution effect due to the new jets. The new jets were designed to pass the same molar rate of fuel into the SUNKISS device but at a higher velocity. The higher velocity entrains more ambient air in through the back of the catalyst pad and permits more complete combustion of propane. However, the additional air adds to the total volumetric flow of gases through the chamber thus diluting the concentrations of VOC, propane and CO somewhat compared with the original system. Calculations were made to adjust the destruction efficiencies to the same basis for the sake of valid comparison of results.

Estimates of the air entrainment rate of the newly modified system were obtained from the head of technical services for SUNKISS, Inc. It had been estimated previously that with a propane supply pressure of 11 inches of water, and with the old jets, about 0.113 cfm (about 0.13 gmoles/min) of ambient air were drawn into the chamber. With the new jets, at 2 psig, the ambient air entrainment rate was about 0.663 cfm or 0.78 gmoles/min. At the lower air flow rates into the chamber (2, 3 or 4 cfm), there is a significant percentage dilution due to the additional primary air brought in with the new system. It should be noted that the calculations of destruction efficiencies that follow depend on the above estimates of air entrainment rates. The outlet air flow rates from the chamber were not measured in this work.

After accounting for the additional air dilution due to the new jets, the VOC destruction efficiencies were calculated for the new jets - new pad system. Also, because chamber residence times at each inlet air flow rate were decreased due to the additional primary air flow, the residence times were re-calculated also. The results are presented in Table 9. As can be seen, if one considers only the inlet air flow rates, there is no apparent

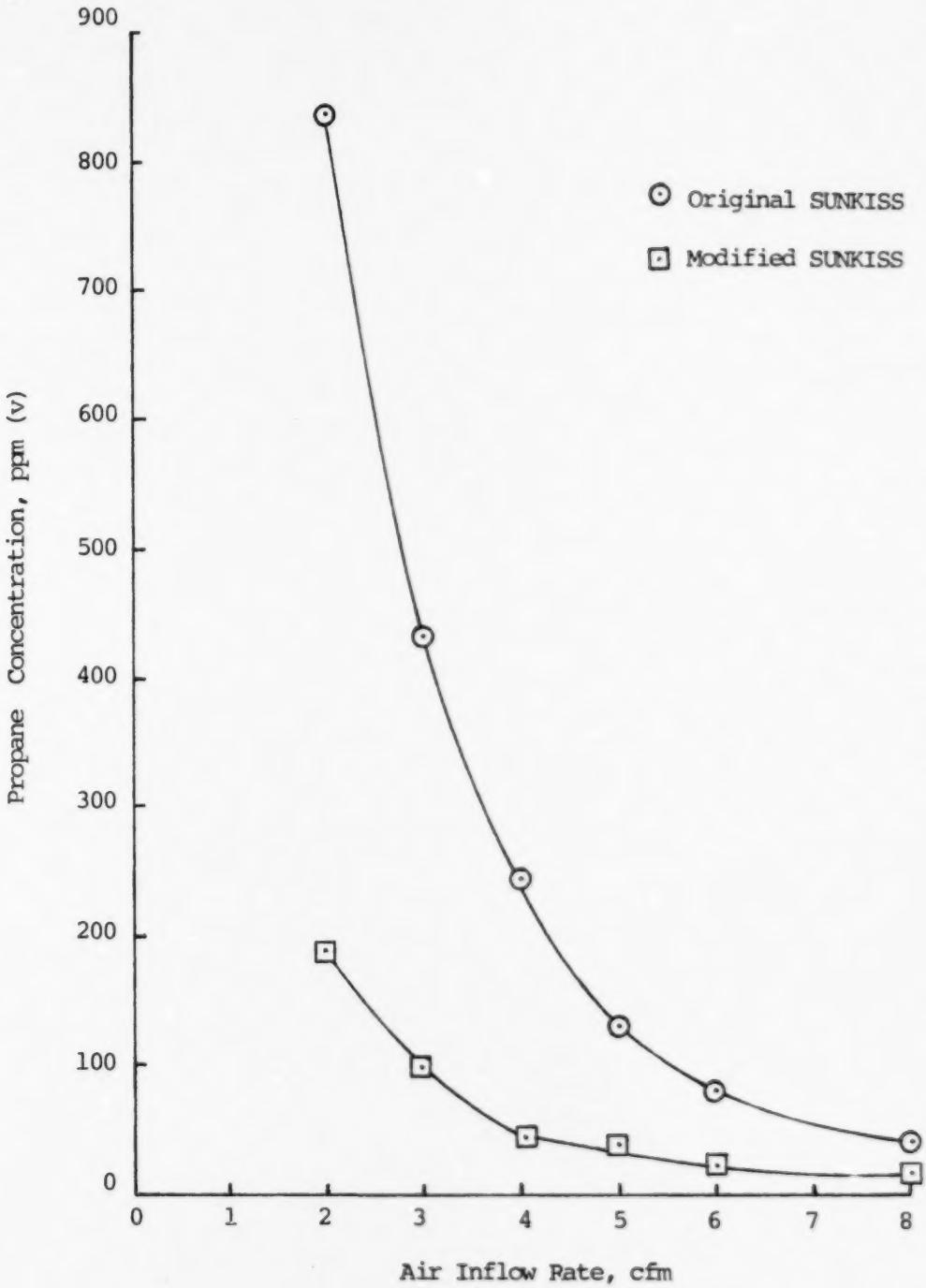


Figure 23 Propane in Exhaust Gases, Original vs. Modified SUNKISS System.

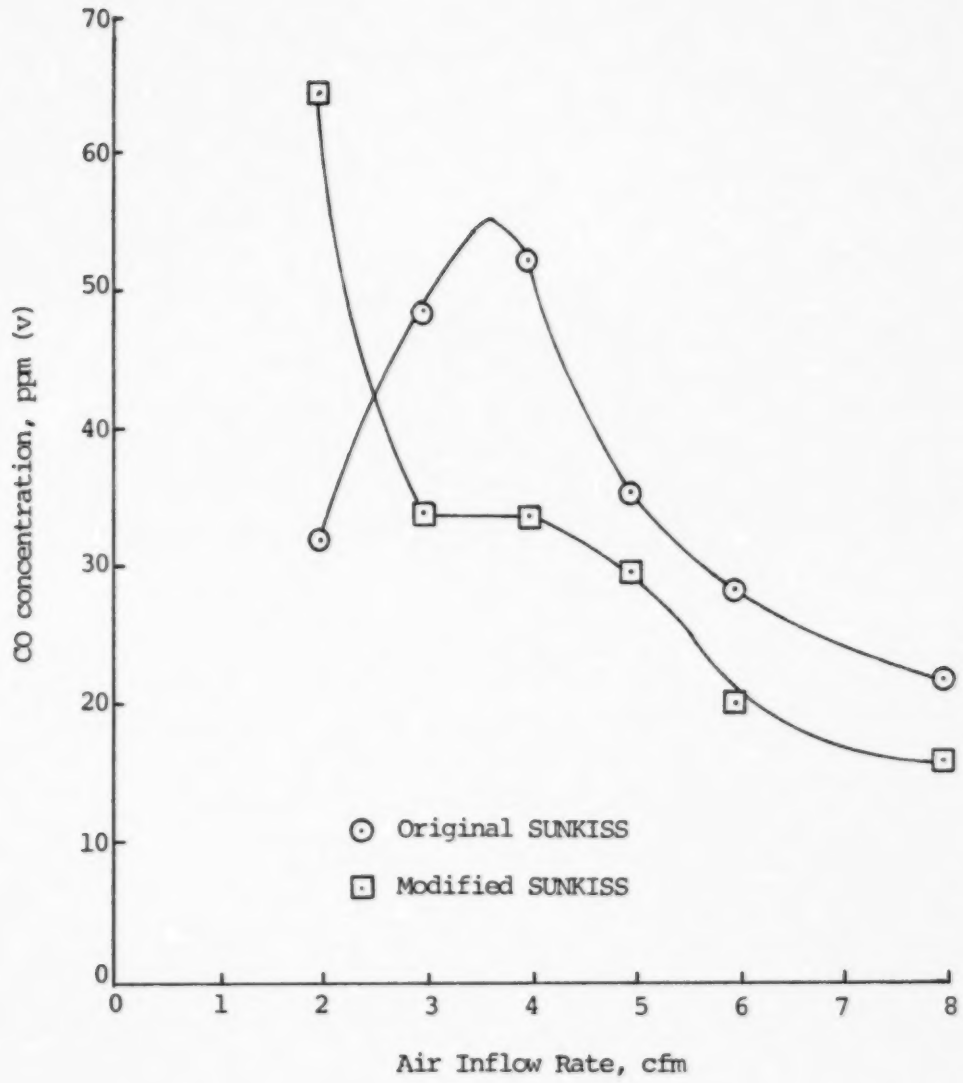


Figure 24 Carbon Monoxide in Exhaust Gases, Original vs. Modified SUNKISS System.

increase in destruction efficiency. However, the fairest comparison is to plot the efficiencies against gas residence time as shown in Figure 25. From this plot, it can be seen that VOC destruction efficiencies did improve with the new system.

TABLE 9

COMPARISON OF MODIFIED SUNKISS DEVICE WITH ORIGINAL SUNKISS DEVICE WITH REGARD TO HEXANE DESTRUCTION

Inlet Air Flow Rate, cfm	Original System		Modified System	
	t_R, min	E, %	t_R, min	E, %
2	13.3	44	10.8	42
3	9.2	38	7.8	36
4	7.0	31	6.2	31
5	5.6	28	5.1	27
6	4.8	21	4.3	23
8	3.6	18	3.3	21

It is interesting to note that the total solvent destruction rate increased with air flow rate even as the efficiency decreased. However, this behavior is an artifact of the test procedure, and would not be observed in a real paint baking oven. In a real oven, the total amount of solvent evaporated would be fixed and depend only on the amount and type of paint on the item being baked. In our latter experiments, the solvent concentration was always controlled to 1000 ppm. At the higher air flow rates, solvent molar inflow rate was higher and, thus, the solvent molar destruction rates were higher, even though the efficiencies were lower. These results are shown in Table 10.

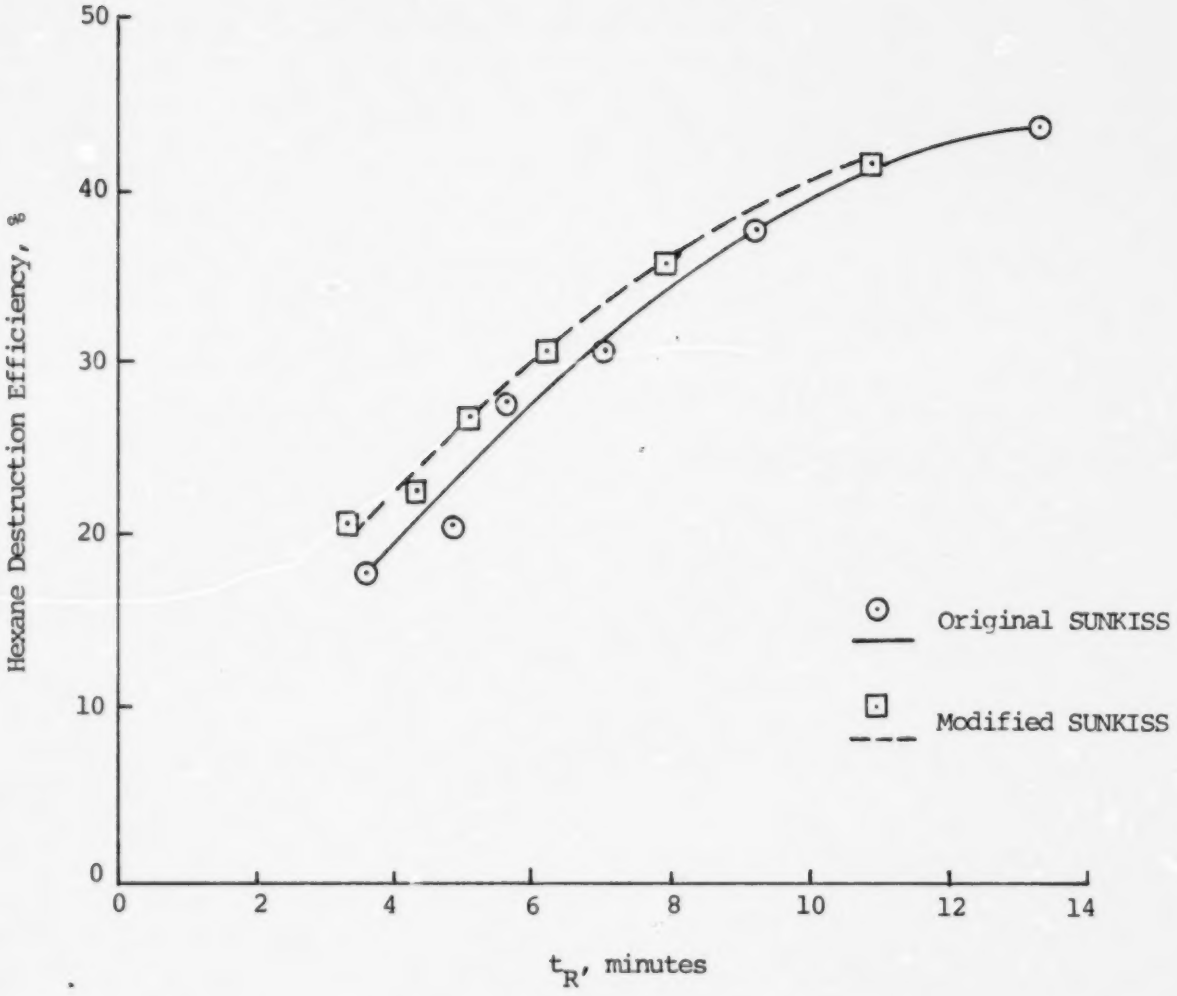


Figure 25 Hexane Destruction Efficiency vs. Gas Residence Time, Original and Modified SUNKISS System.

TABLE 10

TOTAL SOLVENT DESTRUCTION - MODIFIED SUNKISS VS ORIGINAL SUNKISS

Inlet Air Flow Rate cfm	Hexane Input gmole/min	Original SUNKISS		Modified SUNKISS	
		Hexane Destr. Eff. %	Hexane Destr. gmole/min	Hexane Destr. Eff. %	Hexane Destr. gmole/min
2	0.00235	44	0.00103	42	0.00099
3	0.00354	38	0.00135	36	0.00128
4	0.00470	31	0.00146	31	0.00146
5	0.00591	28	0.00165	27	0.00159
6	0.00707	21	0.00148	23	0.00163
8	0.00944	18	0.00170	21	0.00198

Note: Solvent loading increases with air flow rate such that even though efficiencies decline, total destruction rates increase. Such behavior is not representative of a real oven.

In order to fairly compare propane combustion under the new system vs. the old system, the molar flow rates of propane out of the chamber were calculated under each system. The rate of propane into the SUNKISS device was assumed constant at 0.10 gmole/min. The percent of propane combusted was calculated for each system and compared for each inlet air flow rate. The results are shown in Table 11.

In order to fairly compare CO production under each system, the CO generated was expressed as a percentage of all the carbon atoms combusted. That is, first the molar rate of hexane that was destroyed in the chamber was calculated. Then, that rate was multiplied by the number of carbon atoms per molecule of hexane (6). Next, the propane combustion rate was multiplied by the number of carbons in propane (3). The two numbers were summed to give a total carbon atom combustion rate. The molar flow rate of CO exiting the chamber was calculated and divided by the total carbon atom combustion rate to give the CO generation percentage. The calculation equation is presented as equation (6) and the results are presented in Table 12.

$$CO_{gen} = \frac{C_{CO}\, n_e}{6\, E_{Hex} C_{Hex_o} n_o + 3\, E_{Prop} n_{Prop}} \times 100 \qquad (6)$$

where: CO_{gen} = CO generation percentage

C_{CO} = CO concentration in exit gases

n_e = flow rate of exiting gases, gmole/min

E_{Hex} = hexane destruction efficiency

C_{Hex} = inlet hexane concentration

n_o = inlet air flow rate, gmole/min

E_{Prop} = propane combustion efficiency

n_{Prop} = propane inlet flow rate, gmole/min

TABLE 11

COMPARISON OF PROPANE NON-COMBUSTION - MODIFIED SUNKISS VS ORIGINAL SUNKISS

		ORIGINAL SUNKISS				MODIFIED SUNKISS			
Inlet Air Flow Rate cfm	Propane Inflow gmole/ min	Total gas Outflow gmole/ min	Propane Conc ppm	Propane Rate gmole/ min	Percent Combus- tion %	Total gas Outflow gmole/ min	Propane Conc ppm	Propane Rate gmole/ min	Percent Combus- tion %
2	0.10	2.6	840	0.0022	97.8	3.2	190	0.00061	99.39
3	0.10	3.8	435	0.0016	98.4	4.4	100	0.00044	99.56
4	0.10	4.9	245	0.0012	98.8	5.6	46	0.00026	99.74
5	0.10	6.1	130	0.00079	99.21	6.8	41	0.00028	99.72
6	0.10	7.3	80	0.00058	99.42	8.0	20	0.00016	99.84
8	0.10	9.7	40	0.00039	99.61	10.3	16	0.00016	99.84

TABLE 12

COMPARISON OF CO GENERATION-MODIFIED SUNKISS VS ORIGINAL SUNKISS

	ORIGINAL SUNKISS				MODIFIED SUNKISS			
Inlet Air Flow Rate cfm	Hexane Destr. gmole/ min	Propane Destr. gmole/ min	CO Conc ppm	Percent CO Genr. %	Hexane Destr. gmole/ min	Propane Destr. gmole/ min	CO Conc ppm	Percent CO Genr. %
2	0.00103	0.098	32	0.03	0.00099	0.099	64	0.07
3	0.00135	0.098	49	0.06	0.00128	0.099	34	0.05
4	0.00146	0.099	52	0.08	0.00146	0.100	34	0.06
5	0.00165	0.099	35	0.07	0.00159	0.100	29	0.06
6	0.00148	0.099	28	0.07	0.00163	0.100	20	0.05
8	0.00170	0.100	22	0.07	0.00198	0.100	16	0.05

* % CO generation = (moles CO output)/(6 x hexane destr. rate + 3 x propane destr. rate)

SUMMARY OF RESULTS

The solvent destruction capability of the SUNKISS thermoreactor has been tested under laboratory conditions. This catalytic device has been shown to be effective in oxidizing VOC in air in a completely mixed chamber with destruction efficiencies primarily dependent upon air flow rates (residence times) in the chamber. Observed destruction efficiencies ranged from less than 20% to above 50%. The destruction efficiencies were essentially independent of VOC concentration, but were higher for toluene than for either hexane or MEK. The destruction efficiencies were significantly lower than those typical of a final control device (such as a vapor incinerator) but may be high enough to contribute significantly to an overall VOC control program.

Some slight degrees of fuel non-combustion and a very small amount of CO generation were observed, particularly at the lower total air flow rates. The IR generated by the device is absorbed by a painted surface resulting in higher surface temperatures than for unpainted steel. The presence of a painted object in the test chamber increased VOC destruction efficiencies only slightly. The newer system (thicker pad, smaller fuel jets, and higher fuel pressure) resulted in better VOC destruction efficiencies and in more complete propane combustion. The behavior of the device in a full scale oven may be different from that observed in this research due to differences in air flow, parts proximity to the units, higher oven temperatures, or other unidentified factors.